THE FUNCTIONAL ROLES OF THE MOTION PERCEPTION SYSTEMS

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There are several sources of visual information about motion. One is simply the motion on the retina, known as optic flow, caused by motion in the world. Another source of flow-based information is the differences between the optic flow fields of the two eyes, known as interocular velocity differences. Also, there is disparity-based information about motion in the form of the changes in binocular disparity over time that result from motion. This dissertation concerns the results of experimental work to determine the functional differences between the systems that utilize these sources of information. In the context of perception of time-to-contact, flow-based information is used to perceive objects moving at high velocity and disparity-based information is used to perceive objects moving at low velocity. When both are available, these cues are not combined. Instead, humans just rely on the superior form of information, given the object's velocity. In the context of perception of lateral motion, there are greater latencies when processing disparity-based information than when processing flow-based information. Despite this, disparity-based information alone is sufficient to guide perception of, and coordination with, laterally moving objects with no decrease in performance compared to normal viewing conditions that present all sources of motion information. I also discuss work that showed how important motion information is to the perception of static properties like object shape. Specifically, this work demonstrated that both flow- and disparity-based information are necessary for perception of metric shape, as is 45° or more of continuous perspective change. In addition, static disparity

alone is not enough; dynamic changes in disparity are required. Our data suppor1 the way in which the model of R. Foster et al. (2011) combines this infom1ation, although this model needs to be revised because it assumed combination of flow and static disparity, not dynamic changes in disparity. Over the course of this work, I have revisited several well-researched perceptual and perceptuomotor tasks and investigated the roles of flow- and disparity-based motion information in their execution. This work has shed light on both the mechanisms that underlie motion perception and the role of motion perception in other tasks.

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The Functional Roles of the Multiple Motion Systems

At the heart of all study of perception is the question of how organisms are able to correctly interpret exceedingly complex information about exceedingly complex patterns of energy from an exceedingly complex world, and to do so in such a way that this information can be used to guide coherent, stable, and effective behavior. Because of the dynamic nature of the environment and of animals' interactions with it, information specifying motion should be expected to play a vital role. Still, relatively little is known about how humans use this information to perceive the environment and guide behavior. This dissertation will attempt to discern some functional roles of these sources of information and of the systems that exploit them.

Given a single feature of the environment, there are a number of properties that can be perceived about it (distance, shape, slant, etc.) and the ability to detect motion information underlies the perception of many of them. It should be no surprise, then, that humans rely on complex and diverse mechanisms to detect motion information. This diversity results in a high redundancy of function because several systems that are sufficient for detection of motion work in concert. This redundancy allows perception using motion information to be relatively robust to deficits in lower level function and to age more gracefully than most visual functions (Greene & Madden 1987; Hofstetter & Bertsch 1976; Mittenberg, Malloy, Petrick, & Knee, 1994; Norman et al., 2006, 2012).

Motion is ubiquitous in our experience of the world. Even when an observer is "stationary", motion signals generated by their postural sway (Bootsma, 1991) and even eye movements (Bingham, 1993a, 1993b; Martinez-Conde, Macknik, & Hubel, 2004) yield information about their relationship to the environment and about the environment itself. Thus, humans never perceive any feature of the environment without motion present in the visual signal. It should not be surprising, then, that the ability to detect motion is a key feature of the visual system across even seemingly unrelated functions. This primacy of motion is illustrated when it is no longer present. Metzger (1930) presented participants with uniform, featureless fields called ganzfelds. Because a participant's entire visual field was uniform, any relative motion could not be perceived. Even the experience of a single uniform field of color faded. A replication was performed that presented participants with a number of uniform fields, each of a different color. One participant described the experience as "foggy whiteness, everything blacks out, returns, goes. I feel blind. I'm not even seeing blackness. This differs from the black when lights are out" (Cohen, 1957).

Contrast is fundamental to any meaningful perception, and this manipulation eliminated more than just the spatiotemporal contrast of motion. Without contours, difference in luminance, etc., the spatial contrast that is present in still scenes was also removed. Thus, the effective loss of vision could be attributed to a general lack of contrast, not just the lack of motion. At first it might seem easy to selectively eliminate motion from the visual field by presenting a still scene to an observer whose head is held in place. However, this is not sufficient because holding the head in place does not truly stop observer motion because the point of observation is about 11 mm from the center of rotation of the eye (Bingham, 1993a). As a result, directed saccades and microsaccades ensure that even when there is otherwise no relative motion between an observer and a normal, contrast-filled environment, there is relative motion between the point of observation (and thus, for the sake of perception, the observer) and the environment.

These saccades result in changes on the retinae, which in turn provide information about observer motion that can also specify properties of features of the environment.

However, several techniques allow for the stabilization of images by making their motion coincident with microsaccades. This results in lack of change on the retina during presentation of an image. Under such circumstances, the image will fade and disappear (Riggs, Ratliff, Cornsweet, & Cornsweet, 1953). A sort of blindness is experienced, much like when a ganzfeld is presented. Motion is so ubiquitous to human experience of the world that the visual system cannot coherently interpret stimuli without it.

Varieties of Information About Motion

The preceding discussion illustrates how vital motion is to the operation of the visual system, but how is motion detected and how is motion information used? First, it is helpful to make some distinctions about visual motion. I have already characterized it as spatio-temporal change in the visual field that occurs as a result of changes in location of an observer and/or environmental features. This is adequate to discuss visual motion in general, but this definition hints at key distinctions that need to be made.

The Nature of Motion and Visual Information

There are two causes of visual motion: self-motion and environmental motion (but usually both). This distinction is important because the optical events that occur as a result of each differ. Motion of a feature of the environment results in local change at the visual location of that feature, but motion of an observer results in global change across the entire optic array (Gibson, 1950, 1977). In either case, this continuous pattern of change is called optic flow. This dissertation will mostly concern itself with motion in the environment and not self-motion. However, it is informative to first discuss the nature of self-motion detection. Later, this will help to illustrate key points about motion detection in general, but especially about the role that optic flow plays. When an observer moves towards a scene, there is visual expansion of the elements in that scene. This expansion comes in the form of radial outflow at every point in the scene, from a point that corresponds to the observer's direction of heading (Figure 1). This point is called the focus of expansion. If an observer retreats from the visual scene, there is an inflow towards a focus of contraction located opposite of the direction of retreat. Humans use this information to accurately perceive heading within 1 degree of visual angle (Warren, Morris, & Kalish, 1988). In this way, the global flow information that results from self-motion is informative about self-motion, but the local components of this flow are also informative about the scene, i.e. the direction and magnitude of flow resulting from self-motion also specifies the location and structure of local features (Longuet-Higgins & Prazdny, 1980).

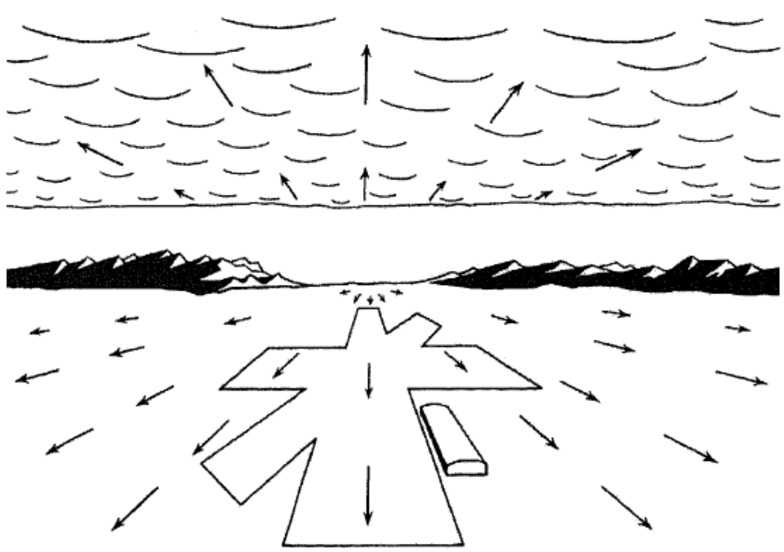

Figure 1. **Global flow from forward observer motion. If traced back, all of the motion vectors would intersect around the horizon, at a focus of expansion, which corresponds to the current heading. Adapted from Gibson (1950).**

Motion of an object causes optic flow at the visual location of that object, which is informative about the speed and direction of this motion. However, local flow alone can yield ambiguous information about the speed and direction-in-depth of an object (Koenderink & van Doorn, 1987). For instance, the same flow pattern could be produced by a large object moving quickly towards the observer from a great distance or by a small object moving slowly from a short distance. However, this is only true if the objects' sizes, speeds, distances, and paths are such that both objects subtend the same visual angle and cover the same optical distance during their movement (Figure 2).

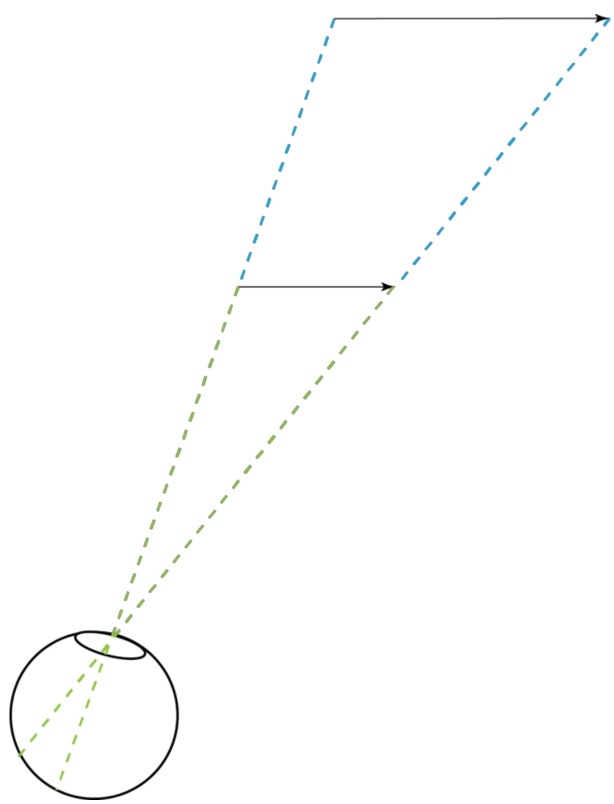

***Figure 2*. Two motion vectors in the environment that produce identical optic flow. As seen illustrated here, a farther object would have to be proportionally larger than the closer object to produce an identical flow pattern.**

Such ambiguity is rarely experienced because it requires such specific constraints and because there are a number of cues that help disambiguate the scene, such as depth. For a given depth, there is only one size and speed that can produce a given flow pattern. There are a number of depth cues, but the role of motion is critical. Relative motion between an observer and features of the environment are ubiquitous and result in systematic changes in the optics that reflect this relationship. Crucially, this relationship does not change equally for each eye, due to the lateral displacement of the two eyes. The resulting difference between the changes in angle from any point in the world to each eye yield several cues during binocular vision that allow continual specification of depth, and thus related properties like size and speed.

Multiple Motion Systems

A key distinction to make is the difference between motion information resulting from change in the optic array at the level of each eye individually (monocular motion information) and motion information resulting from relations across the optic arrays of the two eyes (binocular motion or stereomotion information). This is important because the differences go well beyond the redundancy of information that results from having a second eye. Different forms of information are detected through these means, although some stereomotion information is gained through comparison of the two monocular signals. Two sources of stereomotion information have been shown to play a role, but the field of motion perception has primarily focused on one of these two, changes in binocular disparity across the visual field over time (Cumming & Parker, 1994; Erkelens & Collewijn, 1985; Patterson, Ricker, McGary, & Rose, 1992).

Changes in binocular disparity over time. Binocular disparity arises due to the different direction to any given point from each eye at any point in time. Due to the lateral difference in the points of observation of the two eyes, there is an offset between corresponding points in the images of each eye. The closer a point is to the eyes, the larger the angle that is subtended by its projections to the two eyes, and thus the greater the disparity between the point's locations on each retina (Figure 3). This systematic relation between distance and disparity allows for the specification of depth.

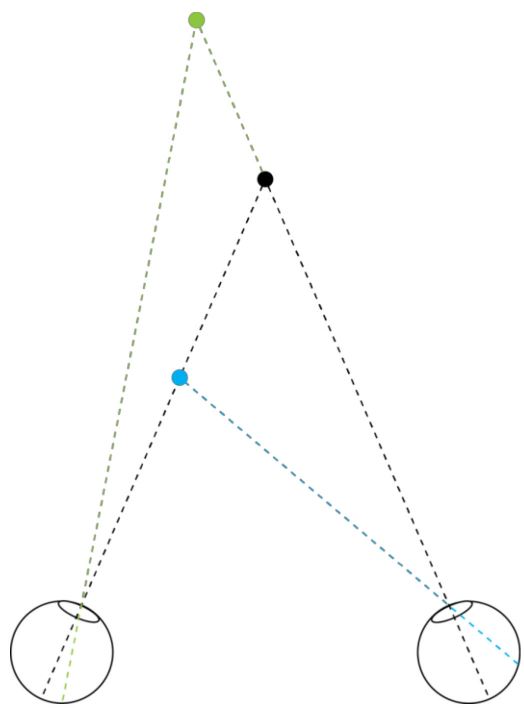

Figure 3. **Optical geometry of binocular disparity. The black point is fixated, so it projects to the center of each retina. The blue point projects to the center of the left retina and the green point projects to the center of the right retina. Because of their different locations, the blue and green points have different disparities, i.e. the distance from the center of the right retina to the projection of the blue point is different than the distance from the center of the left retina to the projection of the green point.**

Motion occurs in three dimensions, and thus information about motion should specify the nature of motion in three dimensions. However, this disparity information is not just used as an additional cue to "fill in the gaps" of the monocular motion system. Comparison of signals from the two eyes yields binocular disparities across the visual field and then the changes in these disparities specify motion. These changes in disparity over time (CDOT) across the visual field specify motion in three dimensions independently of optic flow (Figure 4). This disparity-based information has been shown to be sufficient for performance of a number of tasks, even those traditionally thought of as solely flow-based, like perception of heading (Macuga, Loomis, Beall, & Kelly, 2006). This sort of sufficiency has been shown for both self-motion (e.g. heading) and environmental motion (J. M. Harris & Watamaniuk, 1995).

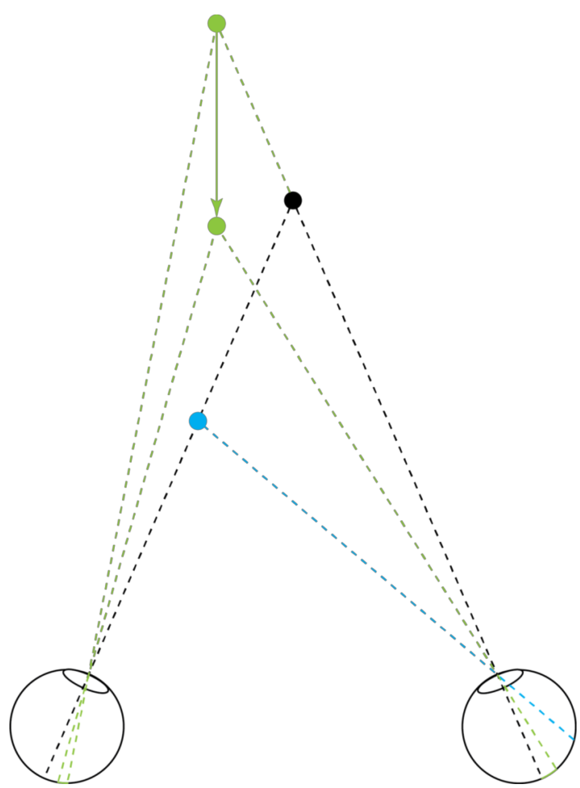

***Figure 4*. Optical geometry of CDOT. When the green point approaches the observer, its location on each retina changes continuously, as does its disparity.**

Interocular velocity differences. The sufficiency of an optical variable for the performance of a task does not preclude contributions from other sources of information. Another binocular cue specifying motion was proposed decades ago (Beverley & Regan, 1973). Much like binocular disparity, this cue arises because of the spatial difference between the two eyes. The optic flow of each eye specifies motion, but depth may not be well recovered from monocular flow alone. Because the eyes have a lateral displacement from one another, there is a systematic difference between the retinal velocities of the eyes. These interocular velocity differences (IOVD) also specify motion in three dimensions (Figure 5).

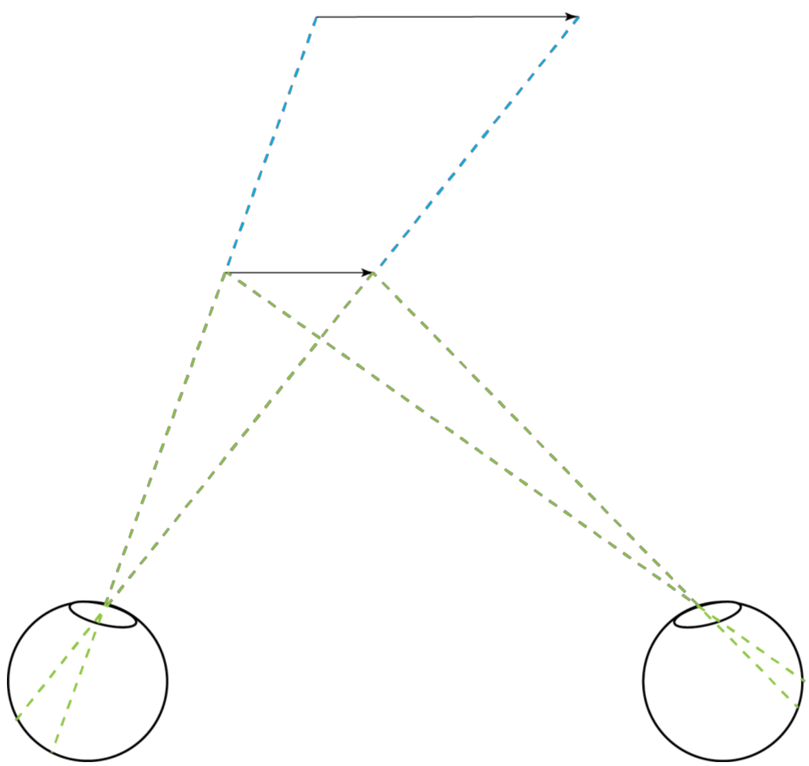

Figure 5**. Optical geometry of IOVD. When viewed monocularly, either motion vector could cause the flow pattern in the left eye. However, when viewed binocularly, only the closer motion vector could simultaneously cause the flow patterns in each eye.**

The cause of IOVD is similar in principal to motion parallax (e.g. the differences in retinal velocities when an observer views two objects at different distances from the side window of a moving car). Instead of two points in the environment being at different depths from a moving observer, as is the case with motion parallax, there is one moving object at different depths from the two eyes. This is true of all points in the visual field, resulting in an interocular velocity difference field. Put another way, this information is based on the disparity between the two eyes' optic flow fields. Although IOVD and CDOT are similar in a number of respects, the key difference is that one is a change of disparity and the other is a disparity of change. Both CDOT and IOVD consist of a disparity (binocular disparity and differences between flow vectors, respectively), the change in which specifies motion in three dimensions. However, the basis of IOVD (monocular flow) already specifies motion, so IOVD is hypothesized to be processed faster (Regan & Beverley, 1973; Tyler, 1971). That is, with IOVD, 3D motion is specified by comparing two motion signals (the monocular flow signals from each eye), but with CDOT the static signals of the two eyes are compared to yield disparity, and then another step is required from the initial comparison across the eyes to yield a motion signal.

The Functional Role of Motion Information

Optic flow fields were first described by Gibson (1950), but it took many years to demonstrate that humans are sensitive to and use optic flow (Braunstein, 1966), and to determine its functionality for perception of heading (Warren et al., 1988), time-to-contact (D. L. Lee, 1976), and more; work which continues to this day. Similarly, CDOT and IOVD were proposed as sources of optic information long ago (Beverley & Regan, 1973; Regan & Beverley, 1973), but establishing their functionality has been a lengthy process. For most of this time, CDOT was the center of investigation, but it still took several decades for significant progress to be made (Patterson, 1999) and much is yet to be determined. Work establishing the utility of IOVD is sparse and most of it is fairly recent (Nefs, O'Hare, & J. M. Harris, 2010; Rokers, Cormack, & Huk, 2009).

CDOT and IOVD yield information about motion. Just because this information is available in the optic array does not mean that humans rely on it, however. There could be reasons that these forms of information are not well-detected by the human visual system, or there could be stronger and/or more reliable cues available. A standard way to show reliance on a source of visual information for a task is to selectively manipulate the proposed information and measure the change in performance, if any, to see if it varied in a systematic manner consistent with the hypothesis. However, selectively manipulating only CDOT or only IOVD is difficult because CDOT and IOVD invariably coincide with one another in natural conditions, as do monocular optic flow and IOVD. If they did not, they would often be in conflict and thus would not be reliable cues.

Clever methods have been used to isolate binocular disparity from a number of other sources of information in the past. The use of a telestereoscope is sufficient in many cases (Wallach & Karsh, 1963). This is a device that uses mirrors or lenses to laterally displace the effective location of the point of observation of each eye. This manipulation increases or decreases the angle between each eye and points in the environment, thus altering binocular disparity throughout the visual field. In this way, binocular disparity can be manipulated without altering some other cues. However, IOVD is also based on interpupillary distance, so it is affected by telestereoscopic manipulation as well. This tight correlation between CDOT and IOVD is not easily broken, so these sorts of simple manipulations are insufficient.

Another common method to determine the utility of a cue is to selectively eliminate the hypothesized information, although this is only definitive if performance cannot continue as a result. If behavior is still effective, it could still be the case that this information is used, but that there are other sufficient sources of information that observers can rely on. Conversely, the source of information can be isolated by removing all other available cues during performance of a task. That way, if performance in the task remains at a high level, it is known that the isolated information that was left available was used. However, it is very difficult to have two sources of highly interrelated information and remove one but not the other.

Isolation of Sources of Stereomotion Information

The technical challenge of isolating binocular disparity from optic flow was met surprisingly early, even before IOVD was known as a source of information, when Julesz (1960) created a display called a stereogram. A common version of this display, the kind that I used, consists of two identical arrays of randomly-positioned dots, one red and one blue, with a small lateral offset. When viewed with red/blue anaglyph glasses, the red dots are only visible to the eye viewing through the red lens and the blue dots are only visible to the eye viewing through the blue lens, and because the patterns are identical besides this offset, each matching pair of red and blue dots is perceived as a single point. From now on, when referring to displays, I will use the word dot to refer to the red and blue dots that are present on screen and I will use the word point to refer to the perceived point specified by a matching pair of red and blue dots. The lateral offset of each pair of matching dots determines the binocular disparity of each resulting point, and thus specifies each point's perceived depth.

This is best illustrated by starting with a single point. Suppose I want to use a stereogram display to have an observer view a point 5 cm behind a computer screen. In order to do this precisely, the location of the observer's eyes must be known. There are significant individual differences in interpupillary distance (IPD), typically falling in the range of 50–75 mm (Dodgson, 2004), so an individual's IPD must be measured in addition to viewing depth and height. Humans typically have significant tolerance for error in the implicit IPD of a stereogram, under which they can still see the image depicted. This is why a group of people with varying IPDs can watch a 3D movie without some individuals losing the percept of depth, but experimental precision is lost if not matching the implicit IPD of a display to the actual IPD of the viewer. Once the locations of the eyes are known, one can project this virtual point back from 5 cm behind the screen to each eye. The locations at which these projections intersect the screen are where the red and blue dots should be placed for the observer to view the point at the intended depth of 5 cm behind the screen. Similarly, if desired depth of the point is in front of the screen, project back to the screen from the eye to find the proper dot locations. Note that this will cause the red and blue dots to appear on opposite sides of each other, e.g. if red dots are to the left of their matching blue dots for points to be viewed behind the screen, red dots will appear to the right of their matching blue dots for points to be viewed in front of the screen (Figure 6).

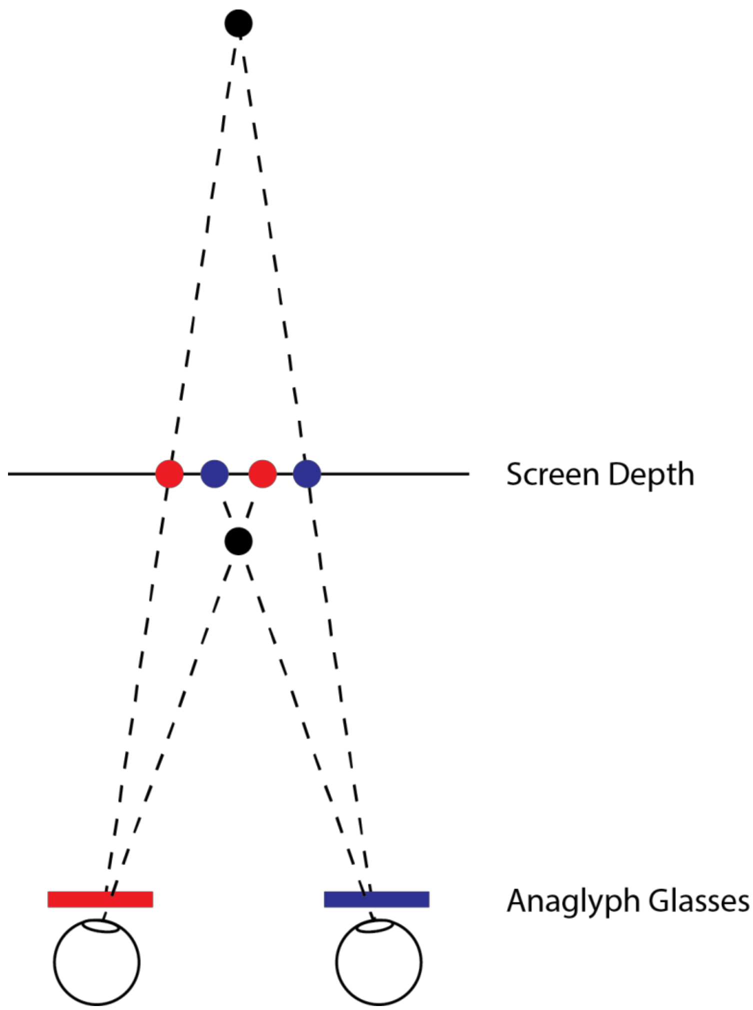

***Figure 6*. Placement of red and blue dots to create virtual points behind or in front of screen. Dots are only visible to the eye viewing through the lens of the same color.**

In full stereogram displays, many of the matching pairs of dots have identical offset magnitudes to specify a background plane at a desired depth. To specify an object at a particular location, the pairs of dots in the corresponding region of the display will have different offsets than the background pairs of dots to specify the desired depth of the object's points. Because the placement of pairs of dots on the arrays is random, this difference in disparity in certain regions is all that defines the existence of objects. When viewed monocularly, or without anaglyph glasses, these displays appear as random arrays of dots.

So far, I have described how a static image can be presented using a stereogram display, but I have yet to explain how these can be used to generated displays that isolate CDOT from monocular flow and IOVD. A video can be made from a series of static stereogram images, allowing for CDOT information to depict motion. In order to eliminate monocular motion and IOVD, each frame of the video uses a new random array of dots. Thus, there is no coherent optic flow across frames. When viewed monocularly, or without anaglyph glasses, these displays appear similar to television static because motion is specified through CDOT alone. When viewed binocularly with anaglyph glasses, the resulting experience is of the specified shape(s) against a background plane and such shapes may translate, expand, or otherwise change according to the programmed changes in disparity across frames.

However, it is more problematic to isolate monocular motion and resulting IOVD from CDOT because this would require a display that provides coherent motion without systematic changes in binocular disparity. It is not clear if this is even possible, but attempts have been made recently to at least degrade binocular disparity without doing so to monocular motion and resulting IOVD (Nefs, et al., 2010; Rokers et al., 2009; Shioiri, Saisho, & Yaguchi, 2000).

Redundancy and Complementarity

Even though disparity- or flow-based information alone would be sufficient in theory, both are used. This becomes advantageous when either disparity or optic flow is absent or degraded. Presumably, this flexibility and resulting stability is why this sort of redundancy can be seen throughout human visual control of behavior, such as the information relied on for targeted walking (Warren, Kay, Zosh, Duchon, & Sahuc, 2001), affordance perception (Wraga & Proffitt, 2000), and size perception (Dixon, Wraga, Proffitt, & Williams, 2000).

CDOT and IOVD may both be sufficient alone for specification of motion, but this does not mean they are equally well suited for all tasks or are used in the same manner. A number of studies have shown that people rely on CDOT (Patterson, 1999) and some suggest CDOT may even be the primary source of stereomotion information (Nefs et al., 2010). However, a number of other studies have shown evidence for the contribution of IOVD as well (Brooks, 2002; Brooks & Stone, 2004; Fernandez & Farell, 2006; Shioiri et al., 2000) and some evidence implies that IOVD may take on a primary role specifying some specific aspects of motion, such as speed of fast-moving (Shioiri et al., 2000) and approaching (Brooks, 2001) objects, and direction discrimination of objects outside the fovea (Czuba, Rokers, Huk, & Cormack, 2010). There are also great individual differences (Wardle & Alais, 2013) and there is evidence that at least some people even use IOVD as the primary source of stereomotion information (Nefs et al., 2010). Such individual differences are a relatively new finding, and it has yet to be determined what causes those people who primarily rely on IOVD to do so. A deficit in detection of binocular disparity is an obvious candidate for at least some of those people because this is a relatively common problem, even in the absence of pathology or poor visual acuity (Richards, 1970).

Given the functions that IOVD appears superior for, it might be helpful to consider the kinds of tasks that would exploit this advantage over CDOT. Recall that

IOVD is processed faster than CDOT. Thus, it can be acted upon faster. When, then, would it be helpful to have the ability to act quickly? Presumably, it would be most important when needing to determine whether or not a situation is dangerous, and then avoid it if it is. Recall that studies have shown a primary role for IOVD in speed perception of fast-moving and approaching objects, and direction discrimination outside the fovea. Direction discrimination outside the fovea should be a fast process so that it can be determined if newly detected objects are approaching, and are therefore a potential threat. Also, for the sake of self-preservation, once it is determined that an object is approaching it is important to quickly determine its speed, especially if it is moving rapidly.

IOVD has been implicated in functions that would ideally serve very simple survival behavior, but CDOT appears to drive a number of more complicated motor behaviors, such as reaching (Anderson & Bingham, 2010). During walking-to-reach behavior, monocular motion information is used to guide general approach to the target, but the more precise reaching portion of the task is carried out using disparity-based information (Anderson & Bingham, 2011; Fath & Bingham, 2012; Fath, Marks, & Bingham, 2014). There is some reason here to hypothesize an evolutionary order to this arrangement. After all, IOVD is based on simpler monocular motion, and the sort of evasive behavior that IOVD is best suited for can be seen in very simple organisms, unlike the behaviors most associated with CDOT. Which source of stereomotion information is relied on depends heavily on the task at hand, so I carried out several studies to determine the functional utility of flow- and disparity-based information for the execution of a number of tasks. These studies are detailed in the following sections.

Testing Functional Differences Between Disparity- and Flow-Based Information

The preceding discussions of the differences in the psychology, physiology, and optics between motion detection with disparity- and flow-based information hint at several functional differences, although many remain untested. Here I will outline experiments that I carried out to discover functional differences across a variety of higher visual and visual-motor functions.

Time-to-Contact

Recall that flow-based information is superior for speed perception of fast-moving objects. However, it is unknown how disparity- and flow-based information compare for slower motion, or for perception of properties of fast motion other than speed. Also, recall that IOVD was found to be superior to CDOT for speed perception of approaching objects. Perception of approaching objects, such as occurs in time-to-contact (TTC) perception, has traditionally been studied using monocular flow and it is known that monocular flow is excellent for this task, so it is not surprising that IOVD, which is based on monocular flow, is good for speed perception of such objects. However, it is unknown how disparity- and flow-based information compare for perception of other properties of approaching objects. To address functional differences concerning both approach and speed of motion, we created an experiment that required participants to discriminate the TTC of objects approaching at a variety of speeds that were specified by only disparity-based information, only flow-based information, or both. A TTC task was chosen because it ties together issues of approach and speed, it relates to both everyday situations and to survival, and there is a wealth of prior research using this task.

An optical variable that is based on monocular optic flow, known as τ, has often been studied for this task (D. L. Lee, 1976). This variable is the ratio of the current visual angle of an object to this angle's current rate of expansion. At any given moment, an object's τ value specifies TTC with the observer if the approach velocity remained constant. Although τ is monocularly available, most human vision is binocular, so it is not surprising to find there are commonly encountered conditions under which perception of TTC is superior with binocular information (Gray & Regan, 2004), such as when viewing small objects (Gray & Regan, 1998) or rotating nonspherical objects (Gray & Regan, 2000).

Anderson & Bingham (2010) proposed a disparity-based τ and further work has confirmed that humans use it to guide execution of a variety of approach behaviors (Anderson & Bingham, 2011; Fath, Marks, Snapp-Childs, & Bingham, 2014). It seems likely, then, that disparity-based motion information plays a role in perception of the TTC of an approaching object. This needs to be demonstrated empirically, though, especially because of the extensive research on flow-based τ. If disparity-based information does play a role in TTC perception, it may differ from that played by flow-based information. Given the advantage for flow-based information with fast motion, there may be an advantage for disparity-based information with slow motion, or both sources could be equally suitable in that case.

Experiment 1. ***Methods*****.** To test disparity-based information's utility for perception of TTC, we ran an experiment similar to that of Todd (1981). We presented participants with stimuli that specified two objects approaching from different distances at different constant velocities. These velocities and starting distances were selected to produce a range of differences in the TTCs of the two objects. During approach, the objects disappeared and participants judged which object would have contacted them first had the objects continued approaching. The displays isolated different sources of motion information, which resulted in three visual conditions: (a) only disparity-based information specified approach, (b) only flow-based information specified approach, or (c) both specified approach. The experiment was run in both slow and fast velocity conditions so we could test what roles different sources of motion information play with respect to velocity of motion.

Participants. Twelve adults (ten female and two male, aged 20–36 years) were recruited to participate in this study. The participants had normal or corrected-to-normal vision, with stereoacuity of at least 80 arcsec crossed disparity as measured by the Stereo Fly Test (Stereo Optical Company, Inc.). All participants gave their informed consent prior to participation. All procedures were approved by and conform to the standards of the Indiana University Institutional Review Board.

Procedure. The procedure was similar to that used by Todd (1981), but now consisted of stimuli that specified motion with disparity-based information only, flow-based information only, or both. The displays were viewed at a distance of 76 cm from a Dell UltraSharp LCD monitor with a resolution of 1920 × 1080 and a refresh rate of 60 Hz. Participants were placed at this viewing distance and told to maintain that location without head movements being mechanically restricted beyond the use of a chinrest. Stimulus presentation, data recording and all data analysis was handled by a custom Matlab toolbox, incorporating the Psychtoolbox (Brainard, 1997; http://psychtoolbox.org). The entire session lasted about one hour.

The stimuli in the disparity-only displays were defined by binocular disparity, which can only be relied on within a relatively close distance from the observer. Thus, the distances that the virtual objects could travel in the disparity-only displays were much smaller than those used by Todd (1981) and in other TTC studies that investigated only optic flow. A wide range of object velocities were required to test our hypothesis, so fewer frames were used in the fast condition across all display types to keep distances covered minimal. The displays consisted of 30 frames per second, so in the fast condition 6 frames were presented within a 200 ms interval and in the slow condition 21 frames were presented within a 700 ms interval. Similar to Todd (1981), the displays depicted two approaching squares. One square was located on the left side of the screen and the other on the right. Both squares appeared at the same time at different depths and each square approached at a different constant velocity. Both squares disappeared during approach at the same moment. Participants were instructed to use the left or right arrow key on a keyboard to select the square that would have contacted them first had both squares continued to approach at their respective constant velocities.

Trials were performed in three viewing conditions, with each condition providing different visual information. In one condition, the approach of objects was only specified by disparity (disparity-only). The disparity-only stimuli were red and blue dynamic random-dot stereograms viewed with anaglyph glasses. These stereograms measured 15 × 15 cm and were set against a dark desaturated background. The magnitude of the lateral offset for each matching pair of red and blue dots was determined based on the corresponding object's location relative to the participant, given the participant's IPD, which was measured before the session. The background plane of these displays defined a background 20 cm behind the screen. For each frame, a new random array of points was created, the correct on-screen locations of the square target objects were determined, given the objects' velocities, and then the disparity of all points within these regions was manipulated to specify the correct depth of the objects.

In a second condition (flow-only), only flow-based information was available. In this condition, random dots were drawn in the display window, as in the disparity-only condition, but with three differences. First, the dots were not re-randomized each frame so there was coherent motion of these dots across frames. Second, the display was viewed monocularly with the dominant eye, which eliminated IOVD, binocular disparity, and resulting CDOT. Thus, only one set of dots was drawn, i.e. there was not a second set of matching dots offset from the first. Lastly, dots were only drawn at on-screen locations depicting the squares, i.e. there were no background dots. In the third condition (combined), anaglyph glasses were used to binocularly view the display, which was the same as in the disparity-only condition with one difference: dots were not re-randomized each frame, leaving monocular motion and resulting IOVD intact.

Each trial was a mathematically accurate simulation of a pair of approaching square objects. Squares had a side length of 4 cm in all trials. Each square started at one of three starting distances: 15, 17, or 19 cm behind the screen. The difference in TTC between the two squares on any given trial was 50, 100, 200, 300, 400, or 500 ms. In the slow condition, the square that would have first contacted the point of observation had a TTC of 3 s, so the square that would have contacted last had a TTC of 3.05, 3.10, 3.20, 3.30, 3.40, or 3.50 s. In the fast condition, the square that would have first contacted the point of observation had a TTC of 0.75 s, so the square that would have contacted last had a TTC of 0.80, 0.85, 0.95, 1.05, 1.15, or 1.25 s. Trials were blocked by visual condition and the order of presentation of visual conditions was counterbalanced across participants. In each block, two trials were performed for each of the six TTC differences from each of the nine left/right starting distance pairs ({15, 17, 19} × {15, 17, 19}). In one of these two trials, the left object would have contacted the point of observation first, and in the other the right object would have contacted first. This resulted in a total of 108 trials per visual condition, presented in a randomized order. For a given trial, once these parameters were determined, the velocities required to produce the selected TTC from the selected starting distances in that block's number of frames were computed to execute the virtual approach. In the slow condition the simulated velocities of the approaching squares ranged 26–32 cm/s and in the fast condition these velocities ranged 73–127 cm/s.

Participants were allowed to repeat any trial by pressing the space bar. They could repeat a trial as many times as they liked before providing a response. Once a response was given, immediate feedback was provided by displaying a white star to the correct side of the display window. Text-based feedback (e.g. "left/right" or "correct/incorrect") was not used because it may have been disruptive to look at the text and then back to the random-dot display before every trial. Our feedback method allowed the participants to focus on the display throughout and detect the feedback in their periphery. The next trial began after the feedback was displayed for 1 s.

Results. Figure 7 shows the proportion of correct responses in the fast condition for each TTC difference for each visual condition. Participants performed comparably in the flow-only and combined conditions, but significantly worse in the disparity-only condition. We performed a two-way repeated measures ANOVA with TTC difference

(50, 100, 200, 300, 40, and 500 ms) and visual condition (disparity-only, flow-only, and combined) as factors. There were main effects of TTC difference ($F(5, 55) = 111.68$, $p <$.$p < .001$) and visual condition ($F(2, 22) = 19.45$, $p < .001$), but no interaction. Contrasts did not show a significant difference between the flow-only and combined conditions.

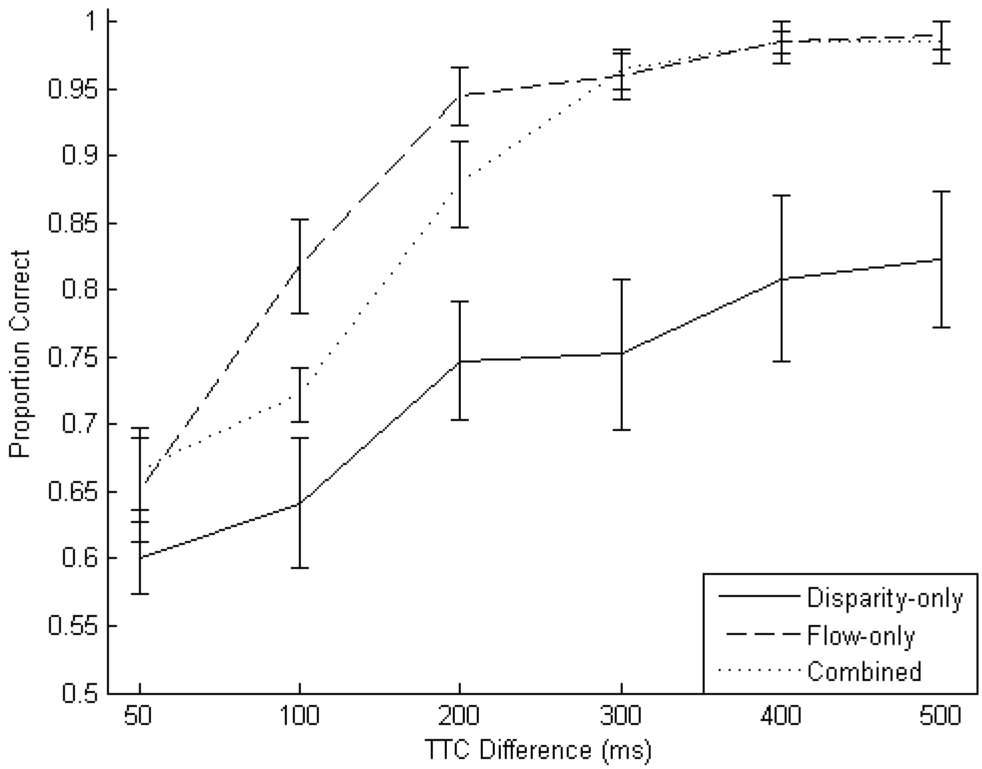

***Figure 7*. Proportion correct in the fast condition as a function of TTC differences for the three information conditions.**

Figure 8 shows the proportion of correct responses in the slow condition for each TTC difference for each visual condition. Participants performed comparably in the disparity-only and combined conditions, but significantly worse in the flow-only condition. We performed a two-way repeated measures ANOVA with TTC difference (50, 100, 200, 300, 40, and 500 ms) and visual condition (disparity-only, flow-only, and combined) as factors. There were main effects of TTC difference ($F(5, 55) = 87.14$, $p <$

.001) and visual condition ($F(2, 22) = 9.31$, $p < .001$), but no interaction. Contrasts did not show a significant difference between the disparity-only and combined conditions.

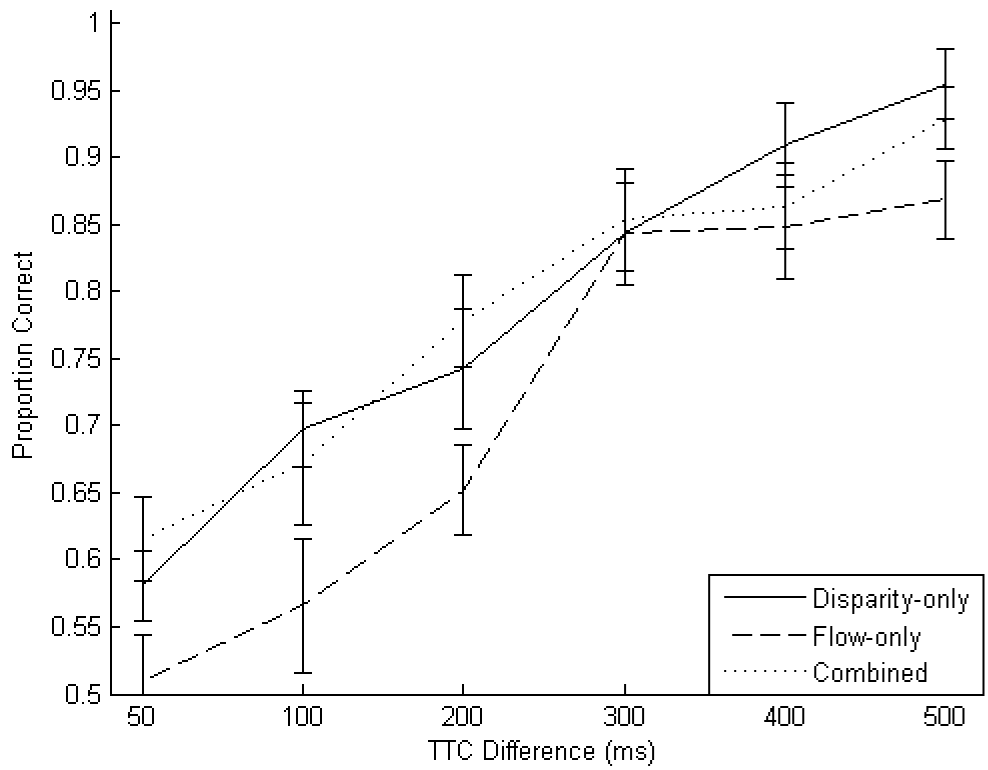

***Figure 8*. Proportion correct in the slow condition as a function of TTC differences for the three information conditions.**

Table 1 shows the average number of repetitions per trial across participants for each visual condition × speed pair. Participants could repeat any trial as many times as they liked before responding. Thus, if a participant had, say, 16 total repetitions for a given visual condition × speed pair, they could have repeated 16 different trials once each or 8 different trials twice each, etc. We performed a two-way repeated measures ANOVA with speed (slow and fast) and visual condition (disparity-only, flow-only, and combined) as factors. There was a main effect of speed ($F(1, 11) = 8.97$, $p < .05$), but no main effect of visual condition and no interaction. Contrasts did not yield any significant differences.

Table 1

Average Repetitions Across Participants for Each Visual Condition × Speed Pair

Visual Condition	Slow	Fast
Flow-only	0.24 (0.19)	0.09 (0.09)
Disparity-only	0.19 (0.20)	0.16 (0.18)
Combined	0.22 (0.32)	0.08 (0.09)

***Note*. Each trial could be repeated more than once and entries indicate average number of repetitions per trial for each visual condition × speed pair. The numbers in parentheses indicate standard deviation.**

Discussion. We confirmed that disparity-based information is used in the perception of TTC. Previous studies suggest that disparity-based information should not be as useful as flow-based information when viewing faster moving objects (Regan & Beverley, 1973; Tyler, 1971). This was supported by our results. Interestingly, we also found that performance was better when viewing slower objects with disparity-based than with flow-based information. It is worth noting that performance with disparity-only stimuli in the fast condition and with flow-only stimuli in the slow condition was still above chance, even in the more difficult trials (i.e., those with smaller TTC differences). Thus, the least reliable source of motion information in any given condition was still informative. On the other hand, performance with all sources of information available was not superior to performance with only the single most reliable source. The main effect of speed in the analysis of trial repetitions seems to be because participants frequently reached very reliable performance (above 95% correct) in the fast condition, but rarely in the slow condition. That is, trial repetition was not necessary when performance was high, which should be expected.

However, even though the finding that flow-based information alone was superior to disparity-based information alone in the fast condition was expected, there is a potential confound that should still be explored. The movement duration for the fast stimuli was very brief (200 ms), so it may have been difficult for participants to fuse the stereogram stimuli and track the objects' motion within that time. Thus, we ran a second experiment where half of the trials were from the same fast condition that was used in the previous experiment and the other half were from a new fast condition in which the objects moved in the same range of fast speeds, but for twice the duration.

Experiment 2. ***Methods*****.** The effect, if any, of increased duration on performance with disparity-only stimuli was the primary interest, as this would tell whether reduced performance with disparity-only stimuli in the fast condition of Experiment 1 was a product of the high speeds or the short duration. However, we ran all three of the visual conditions from Experiment 1 to also see if the increased stimulus duration affected performance in any visual conditions.

Participants. Ten adults (eight female and two male, aged 22–37 years) were recruited to participate in this study. The participants had normal or corrected-to-normal vision, with stereoacuity of at least 80 arcsec crossed disparity as measured by the Stereo Fly Test (Stereo Optical Company, Inc.). All participants gave their informed consent prior to participation. All procedures were approved by and conform to the standards of the Indiana University Institutional Review Board.

Procedure. The apparatus and procedure was identical to that of Experiment 1, with the exception that the slow condition was replaced by a condition with the same velocities as the fast condition, but with twice the stimulus duration (long). The original fast condition that we have replicated here will be referred to as the short condition. The displays in the long condition consisted of 12 frames presented within a 400 ms interval. The background plane was specified at 48 cm behind the screen. Each square started at one of three starting distances: 30, 37.5, or 45 cm behind the screen. The square that would have contacted the participant first had an initial TTC of 1 s, so the square that would have contacted last had an initial TTC of 1.05, 1.10, 1.20, 1.30, 1.40, or 1.50. Like in Experiment 1, trials were blocked by visual condition and the order of presentation of visual conditions was counterbalanced across participants.

Results. Figure 9 shows performance in all conditions. Our primary interest is if duration affected performance with the disparity-only stimuli. To test this, we performed a two-way repeated measures ANOVA with TTC difference (50, 100, 200, 300, 40, and 500 ms) and duration (short and long) as factors. There was a main effect of TTC difference ($F(5, 45) = 3.15$, $p < .05$) but no effect of duration and no interaction. Similarly, we performed two-way repeated measures ANOVAs on the data from the two other visual conditions with TTC difference (50, 100, 200, 300, 40, and 500 ms) and duration (short and long) as factors. In the flow-only condition, there was a main effect of TTC difference ($F(5, 45) = 118.31$, $p < .001$) but no effect of duration and no interaction. In the combined condition, there was a main effect of TTC difference ($F(5, 45) = 96.72$, $p < .001$) but no effect of duration and no interaction.

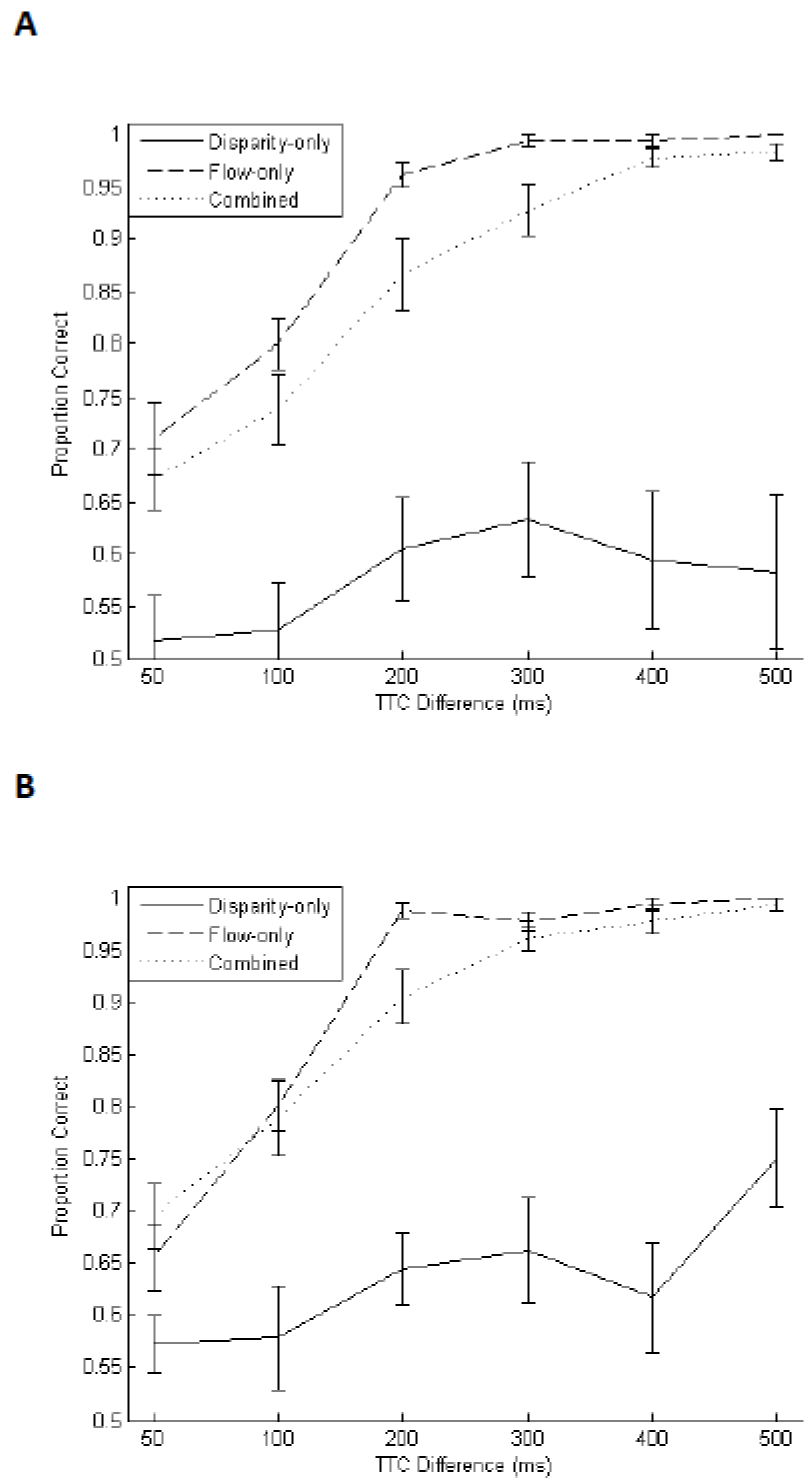

Figure 9. **Proportion correct in the short condition (A) and long condition (B) as a function of TTC differences for the three information conditions.**

Discussion. Experiment 2 found no evidence for an increase in performance with an increase in duration when viewing the disparity-only stimuli. Thus, the finding from Experiment 1 that performance was poor in the fast condition with disparity-only stimuli is supported, and this result was not an artifact of the short stimulus duration. Stability of perception of TTC across a variety of motion speeds is functionally advantageous. This stability is achieved by relying on different sources of motion information under different circumstances.

With variation in speed of motion, we found that flow-based information is used primarily for perception of fast motion of approaching objects and disparity-based information for slower motion. In the context of the visual control of approach behaviors, monocular information about TTC has been shown to be used to control approach during tasks like braking (Warren, 1998) that often involve faster motion and stereo information about TTC has been shown to be used to control approach during tasks like reaching (Anderson & Bingham, 2010; Watt & Bradshaw, 2003) that typically involve slower motion. The results of this study are consistent with these prior findings.

Visually Guided Manual Coordination

We have seen in our work and the work of others that a particular source of motion information may be preferred for a task due to a spatial advantage (e.g. the location of an object in the visual field) or a spatiotemporal advantage (e.g. velocity of object motion). Next we look at potential temporal advantages. Zannoli, Cass, Alais, & Mamassian (2012) performed a study that measured the processing latencies for flow- and disparity-based information during different kinds of motion. This was done by comparing the time required to process motion when viewing disparity-defined stimuli to the time required for stimuli defined by both luminance and disparity. They measured the time lag at which participants perceived the oscillations of the amplitude of a tone to be inphase with the oscillations of movement of visual stimuli that were either moving laterally or solely in depth. They found that perception of disparity-defined visual stimuli moving laterally lagged behind perception of the auditory tone by 90–170 ms, but only by ~60 ms for disparity-defined stimuli moving in depth. The lag for luminance-defined stimuli was ~50 ms when moving laterally and ~40 ms when moving in depth.

The finding that lateral motion of disparity-defined stimuli was processed slower raises the question of how suited disparity-based information is for tracking laterally-moving objects. The visual system might rely entirely on flow-based information, when it is available, for laterally moving objects because the lag from disparity is prohibitive in those conditions. Of course, object motion is rarely purely lateral, but it could be the case that the lateral component of 3D object motion is perceived without using disparity. However, in principle, a disparity-only motion perception system could still function near-optimally in guidance of most day-to-day behavior, even in the rare instances that involve purely lateral movement. If all motion is perceived with the same lag, coordinated behaviors such as typing, reaching, or sewing should not be affected. Even interactions with independently-moving objects, such as when grasping a rolling ball, might not be problematic unless an object is moving unpredictably. However, whether or not performance would degrade for interactions with laterally-moving stimuli in the absence of optic flow is an empirical matter.

The purpose of this study was to determine if disparity-based information is sufficient to guide coordination with purely lateral motion. To test if the increased lag found by Zannoli et al. (2012) presents enough of an impediment to affect visually-guided coordination with laterally-oscillating stimuli, we tested how people performed in a rhythmic coordination task with an independently-moving object in lateral motion, both when the stimulus was only defined by disparity and when it was defined by both disparity and luminance. If we found decreased performance with the disparity-defined stimuli, we could conclude that disparity-based information is not sufficient, likely due to increased visual lag. There is a task that has been studied substantially in the coordination literature that consists of oscillatory lateral motion. Participants view a filled circle oscillating laterally on a screen and use a joystick to move another circle in a specified target relative phase with the computer-controlled circle (Wilson, Collins, & Bingham, 2005). We have adapted this task for use in the current study, using target relative phases of 0° (inphase), 180° (antiphase), and 90° (Figure 10). The task was performed with both luminance-defined and disparity-defined stimuli. Luminance-defined stimuli provided participants with both flow- and disparity-based information, but disparity-defined stimuli only provided participants with disparity-based information. If disparity-based information is sufficient to guide coordination in this task, we should see no difference in performance between these two conditions. Performing 90° is more difficult than 180°, which is in turn more difficult than 0°. It could be the case that increased lag of disparity-defined stimuli is not problematic for easier relative phases, but is for more difficult ones. Using multiple relative phases allowed us to test if task difficulty affected participants more when coordinating with disparity-defined stimuli.

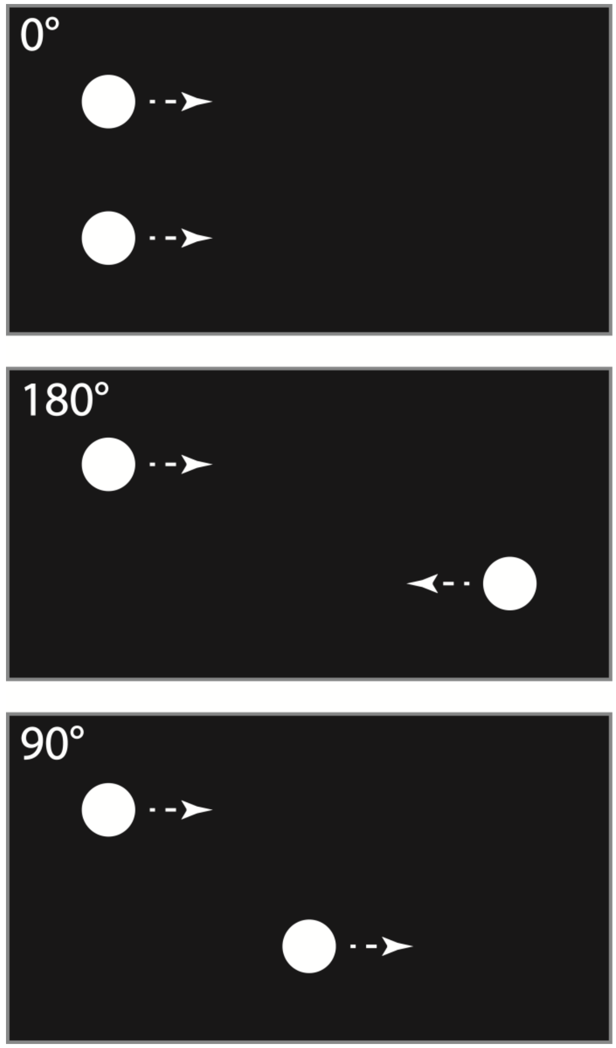

Figure 10. **Illustration of the three relative phase relations used. Each shows the top, computer-controlled circle at the leftmost possible location beginning rightward movement, and the bottom circle at the corresponding location it would need to be to produce the target relative phase.**

Methods. ***Participants*****.** Twelve adults (five female and seven male, aged 25–36 years) were recruited to participate in this study. The participants had normal or corrected-to-normal vision, with stereoacuity of at least 80 arcsec crossed disparity as measured by the Stereo Fly Test (Stereo Optical Company, Inc.). All participants had previously been trained in the task as part of their participation in a prior study. This was done because many people are unable to reliably produce 90° relative phase without training, regardless of viewing conditions. All participants gave their informed consent prior to participation. All procedures were approved by and conform to the standards of the Indiana University Institutional Review Board.

***Procedure*.** The procedure was nearly identical to those used by Coats, Snapp-Childs, Wilson, & Bingham (2013) and by Coats, Wilson, Snapp-Childs, Fath, & Bingham (2014). Each stimulus was displayed on a Dell UltraSharp LCD monitor with a resolution of 1920 × 1080 and a refresh rate of 60 Hz, viewed from a distance of 76 cm. A Logitech Force 3D Pro joystick (force feedback feature disabled) was attached via USB. The joystick was placed off to the side of the display that corresponded to the participant's dominant hand and was controlled by that hand. The computer presented a display showing two filled circles, one above the other, against a black background. During task demonstrations, both circles were under the control of the computer. During trials, the top circle was under the control of the computer and the bottom was under the control of the participant via the joystick. Computer controlled circles in both instances oscillated laterally with a frequency of 0.75 Hz. The amplitude of this movement was 15 cm and each circle was 3 cm in diameter. Stimulus presentation, data recording, and all data analysis were handled by a custom Matlab toolbox, incorporating the Psychtoolbox (Brainard, 1997; http://psychtoolbox.org).

Participants first viewed an 8 s task demonstration of the two circles in 0° relative phase. Then they attempted to produce and maintain 0° relative phase for five 20 s trials, the first of which was a practice trial and was not analyzed. This was done by moving the joystick from side to side to control the bottom circle and coordinate its phase with that of the computer-controlled top circle. This procedure was then repeated for the 180° and 90° target relative phase conditions. All participants performed this block of three target relative phases using two different types of stimuli, one that provided participants with both flow- and disparity-based information (luminance-defined), and one that only provided participants with disparity-based information (disparity-defined). Both the luminance-defined block and the disparity-defined block were performed in the same session, with the order of blocks counterbalanced across participants.

In the luminance-defined condition, the circles were white on a black background. The disparity-defined stimuli were red and blue dynamic random-dot stereograms viewed with anaglyph glasses. These arrays of dots were 15 × 15 cm squares. Most of the dots defined a background at screen depth. For each frame, the correct location of the circles was determined and then the disparity of all points within these circles was manipulated to specify a depth of 5 cm in front of the screen. This difference in disparity of points is all that defined the circles.

Data Analysis. The position time series for both circles from each trial were filtered using a low-pass Butterworth filter with a cut-off frequency of 10 Hz. These position time series were numerically differentiated to yield velocity time series for each circle. These were used to compute time series of relative phase, the key measure of coordination between the two circles of a given trial. To assess the stability of coordination over the course of a trial, we measured the proportion of time on task (PTT). A participant was determined to be on task at a given instant if the relative phase of the two circles at that moment fell within a ±20° window of the target relative phase. We averaged PTT, for each participant, over the trials performed in a given condition.

We chose PTT as the primary performance measure because, in human movement, stability is not independent of mean relative phase. Thus, overall movement variability (e.g. the standard deviation of mean relative phase or mean vector length) is confounded with the actual relative phase produced. Coordination stability at 90° can be artificially elevated if participants spend time producing some other relative phases. This is a common occurrence because the 0° and 180° relative phases are natural attractors (Kelso, 1984; Wilson et al., 2005; Zanone & Kelso, 1992). Using PTT as a performance measure allowed us to address this problem (Coats et al., 2014; Snapp-Childs, Wilson, & Bingham, 2011).

Results. All participants were previously trained in the task during a prior study using luminance-defined stimuli, so we expected competent performance in that visual condition. We expected participants to correctly perceive the disparity-defined stimuli and for their resulting performance to be comparable to their performance with the luminance-defined stimuli. Participants performing a relative phase coordination task typically perform best when attempting to produce 0°, followed by 180°, and then the intermediate phase of 90° (Kelso, 1984). Thus, we expected performance as measured by proportion of time on task (PTT) to be best when attempting to produce 0° relative phase. With feedback, participants can train to perform 90° as well as they can perform 180°, but still not as well as 0° (Wilson, Snapp-Childs, Coats, & Bingham, 2010). Thus, we expected performance of 180° and 90° to not be as high as for 0°, but still good because participants had previous training. This was predicted for both types of stimuli.

Figure 11 shows performance for both stimuli, in all target relative phases, measured as PTT within 20° of the target relative phase. The figure shows that participants performed comparably in the disparity-defined and luminance-defined conditions. In addition, as predicted, participants performed comparably in the 90° and 180° conditions, but not as well as they did in the 0° condition. We performed a two-way repeated measures ANOVA with stimulus type (luminance-defined and disparity-defined) and target relative phase (0°, 90°, and 180°) as factors. There was a main effect of target relative phase ($F(2, 22) = 20.55$, $p < .001$), but no main effect of stimulus type and no interaction.

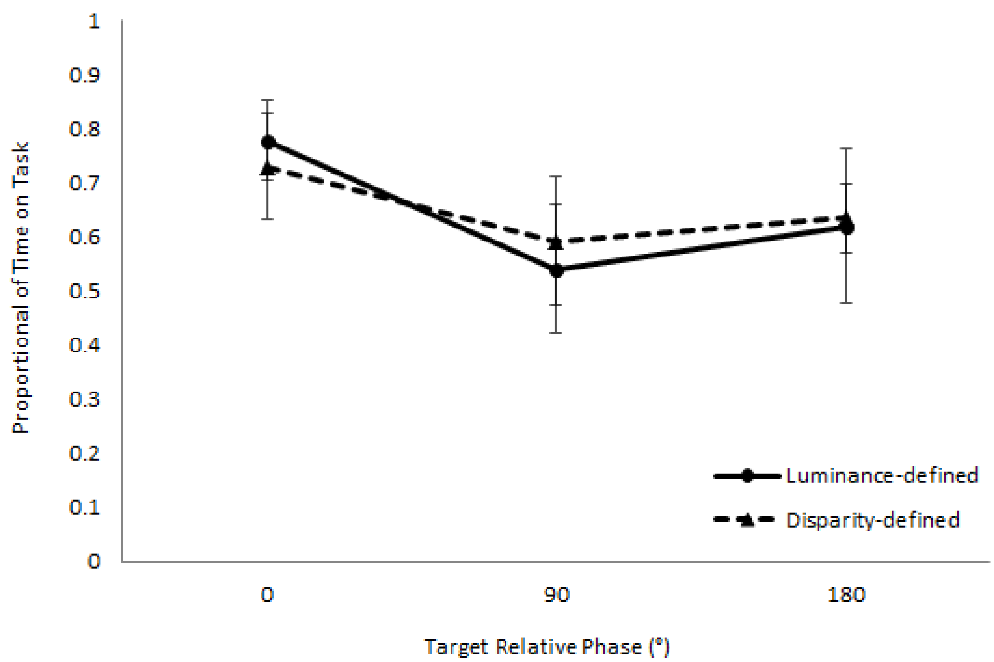

Figure 11. **Performance across target relative phase for both stimulus types. Being on task at a given instant was defined as being within 20° of the target relative phase. PTT was averaged across participants in each condition (luminance-defined and disparity-defined) for each target relative phase (0°, 90°, and 180°). The stimuli in the luminance-defined condition provided both flow- and disparity based information. The stimuli in the disparity-defined condition provided only disparity-based information. Error bars represent standard deviation.**

Discussion. Perception operates in the service of action. The implications of the study of perception are best understood in the context of how they bear on interaction with a dynamically-changing environment. To execute stable behavior, the human visual system relies on multiple sources of information about motion, although one source is sufficient under most conditions. In the current study we show that, under stable conditions, disparity-based information is sufficient to guide perception of, and coordination with, laterally moving objects. This is true despite the greater latencies when processing disparity-based information about lateral motion than when processing flow-based information about lateral motion. Both objects are perceived with the same latency, so small increases in latency will affect perception of both objects equally. This shouldn't hinder performance coordinating the relative phase of these objects when motion is regular, as was the case here. However, unpredictable changes in direction or speed should negatively impact performance.

Shape Perception

One of the more useful properties of an object to perceive is its shape. At first glance, this is a property that would seem fairly divorced from motion. However, I will discuss later how motion information is surprisingly critical for accurate and precise perception of shape. Also, shape perception is important for execution of dynamic interaction with the environment. Countless objects are encountered throughout daily life and it is often enough to perceive the shape of objects in general terms. For example, it would be helpful for an observer to see that a clock is round, but its relative width, height, and depth in relation to each other are not particularly important. However, if the observer intends to pick up the clock or otherwise interact with it, accurate and precise perception of shape is critical.

To pick up an object, the initial feedforward portion of the reach is rapid, until the hand is in view. Now that the hand is in view, control is online and the reach decelerates to allow for soft contact with the target object. After this online approach phase begins, visual information about object shape guides the formation of the hand into a configuration that will allow it to close on the target with precise finger placement (Jeannerod, 1984, 1988; Mon-Williams & Bingham, 2011; Schettino, Adamovich, & Poizner, 2003). The fingers open to create a grasp aperture that reaches its maximum size about 75% of the way through a reaching movement's time, which coincides with the peak deceleration (Jeannerod, 1986). The spatial and temporal structure of the hand's configuration during approach is adaptable and varies with perception of relevant object properties, like size and shape (Jeannerod, 1988). For example, whenever possible, the maximum grasp aperture during a reach exceeds the maximum object dimension, so this extent must be perceived if collisions are to be avoided (Bingham, Snapp-Childs, Fath, Pan, & Coats, 2014). The timing of the maximum grasp aperture also scales with object size, with later occurrence for larger objects (Mon-Williams & Bingham, 2011).

The rest of the movement is characterized by low velocity and low deceleration while the grasp aperture closes (Jeannerod, 1984; Paulignan & Jeannerod, 1996). After the hand opens to a maximum grasp aperture, the hand begins to close and visual information about object shape guides finger placement during the grasp (Bingham, Hughes, & Mon-Williams, 2008; Cuijpers, Brenner, & Smeets, 2006; Ganel & Goodale, 2003; Y.-L. Lee, Crabtree, Norman, & Bingham, 2008). As the fingers reach the same depth as the target, the grasp aperture is larger than the width of the target and remain at that depth as the fingers close (Bingham et al., 2008; Y.-L. Lee et al., 2008). Like maximum grasp aperture, this terminal grasp aperture scales with perceived object size. However, the relative object properties that determine the maximum and terminal grasp apertures are different. Terminal grasp aperture simply scales with the perceived width of the object at the points to be grasped. Maximum grasp aperture scales with the maximum dimension of the object, reflecting a collision prevention strategy (Mon-Williams & Bingham, 2011), so it is important that a target's extents are perceived accurately. Different properties of object shape influence the form of reaching and grasping movements at each stage, so if any of these properties were incorrectly perceived it could result in collision, or inefficient compensatory deceleration to avoid collision, due to improper scaling or timing of a portion of the movement.

The example of reaching-to-grasp illustrates how critical the accurate and precise perception of shape is, even for relatively simple motor tasks. However, the prevailing view in the shape perception literature has been that humans are unable to perceive an object's metric shape, i.e. humans can accurately compare extents in the same dimension (e.g. width or depth) but not across dimensions. This view is supported by much experimental evidence (Battro, Netto, & Rozestraten, 1976; Brenner & van Damme, 1999; Cuijpers et al., 2006; Foley, 1972; Foley, Ribeiro-Filho, & Da Silva, 2004; Indow, 1991; Koenderink, van Doorn, Kappers, & Todd, 2002; Koenderink, van Doorn, & Lappin, 2000; Lappin & Ahlström, 1994; Norman, Todd, Perotti, & Tittle, 1996; Perotti, Todd, Lappin, & Phillips, 1998; Scarfe & Hibbard, 2006; Shepard, 1964; Tittle, Todd, Perotti, & Norman, 1995; Todd & Bressan, 1990; Todd & Norman, 1991). However, the procedures and apparatuses used in these studies frequently lacked ecological validity in several ways, such as restriction of the head movement of participants. This lack of freedom of head movement is troubling because past experiments have shown that performance in a number of tasks that rely on shape perception, such as reaching and grasping, suffers when head movement is restricted or manipulated (Biguer, Donaldson, Hein, & Jeannerod, 1988; Biguer, Prablanc, & Jeannerod, 1984; Carnahan, 1992; Marteniuk, 1978; Prablanc, Echallier, Jeannerod, & Komilis, 1979; Prablanc, Echallier, Komilis, & Jeannerod, 1979).

However, humans still do not perceive metric shape when they are allowed free head movement while judging the shape of objects (Lind, Bingham, & Forsell, 2003), so it would seem that these restrictions of head movement are unlikely to have prohibited the perception of metric shape on their own. Perhaps the freedom of participants to move their heads was not effective at enabling metric shape perception because the magnitude of such movements was insufficient. When interacting with the environment, humans do not typically sit and then make visual contact with a target object to be acted on. Instead, as an individual enters and moves through the environment, objects and their relationships to the environment are perceived continuously from a continuously changing perspective. When continuous perspective changes of 45° or more are experienced, which they frequently are because of locomotion through the environment, metric shape can be perceived (Bingham & Lind, 2008). This finding holds for a number of tested variations in the nature of the objects and perspective changes, e.g. both symmetric and asymmetric objects, various speeds of perspective change, and perspective changes not centered on the target object (Lind, Y.-L. Lee, Mazanowski, Kountouriotis,

& Bingham, 2014). This study also found that continuous perspective change exceeding 45° does not produce any additional benefit compared to exactly 45°. The continuous nature of such perspective changes is critical, as Bingham & Lind (2008) found that discrete perspective changes, even those much greater than 45°, are ineffective at enabling metric shape perception.

These findings have been extended to related domains. For example, small qualitative changes in object shape cannot be used for object recognition (Biederman & Bar, 1999; D. H. Foster & Gilson, 2002; Perotti et al., 1998), unless continuous perspective change of 45° or more is experienced (Y.-L. Lee, Lind, Bingham, & Bingham, 2012). Similarly, feedforward reaches are generally inaccurate (Brenner & van Damme, 1999; Cuijpers et al., 2006; Hibbard & Bradshaw, 2003; Y.-L. Lee et al., 2008; Melmoth & Grant, 2006; Watt & Bradshaw, 2003), but sufficient perspective change results in accurate feedforward reaches (Y.-L. Lee & Bingham, 2010). Importantly, feedforward reaches continue to be accurate with significant delays between perspective change and performance. Accurate performance even persists over the course of consecutive reaches to multiple objects after a single change in perspective. These results would seem to imply that continuous perspective change of 45° or more does not just provide instantaneous information about an attended object's shape. Rather, these conditions yield accurate perception of space that persists over some time.

The above findings concerning the utility of continuous perspective change involved stimuli that were either real objects or virtual objects viewed stereoscopically to mimic the three-dimensional nature of real-world viewing conditions. Thus, both flow-based and disparity-based information about the relative motion between the object and observer was always available to all participants. Further work is required, then, to determine what visual information underlies metric shape perception through continuous perspective change. We tested the utility of flow-based and disparity-based information by presenting participants with displays that either isolated one of these sources of information or presented all of them. These displays depicted a rotating asymmetric pentagonal prism, like the displays used by Lind et al. (2014). Participants judged the shape of the prism by adjusting a two-dimensional response figure to match its cross-section.

Experiment 1. ***Methods.*** *Participants*. Ten adults (seven female and three male, aged 20–36 years) were recruited to participate in this study. The participants had normal or corrected-to-normal vision, with stereoacuity of at least 80 arcsec crossed disparity as measured by the Stereo Fly Test (Stereo Optical Company, Inc.). All participants gave their informed consent prior to participation. All procedures were approved by and conform to the standards of the Indiana University Institutional Review Board.

Stimuli and Procedure. Stimuli were similar to those used in Experiment 3 of the study conducted by Lind et al. (2014), except the manner in which the objects were rendered. Their stimuli specified the target objects using contours and random line-element texture, but we used random-dot displays. Additionally, all of their stimuli provided both flow- and disparity-based information throughout but in the current study, participants also viewed stimuli that provided only flow- or disparity-based information, just like in the TTC experiments. The stimuli were displayed on a Dell UltraSharp LCD monitor with a resolution of 1920 × 1080 and a refresh rate of 60 Hz. Stimulus presentation, data recording and all data analysis was handled by a custom Matlab toolbox, incorporating the Psychtoolbox (Brainard, 1997; http://psychtoolbox.org). The entire session lasted about one hour. The total area of the random-dot display was 15 × 15 cm. Most of this display defined a background 18 cm behind the screen. In all information conditions, the stimulus consisted of an asymmetric pentagonal prism (Figure 12) continuously rotating back and forth about a vertical axis through the center of the prism. This rotation axis was located 10 cm behind the screen and the magnitudes of rotation for a single cycle of rotation were 15, 45, and 75°. Participants viewed the displays from a distance of 76 cm. To obtain the viewing angle of 16° used by Lind et al. (2014), participants viewed from a height 25 cm above the top surface of the prisms.

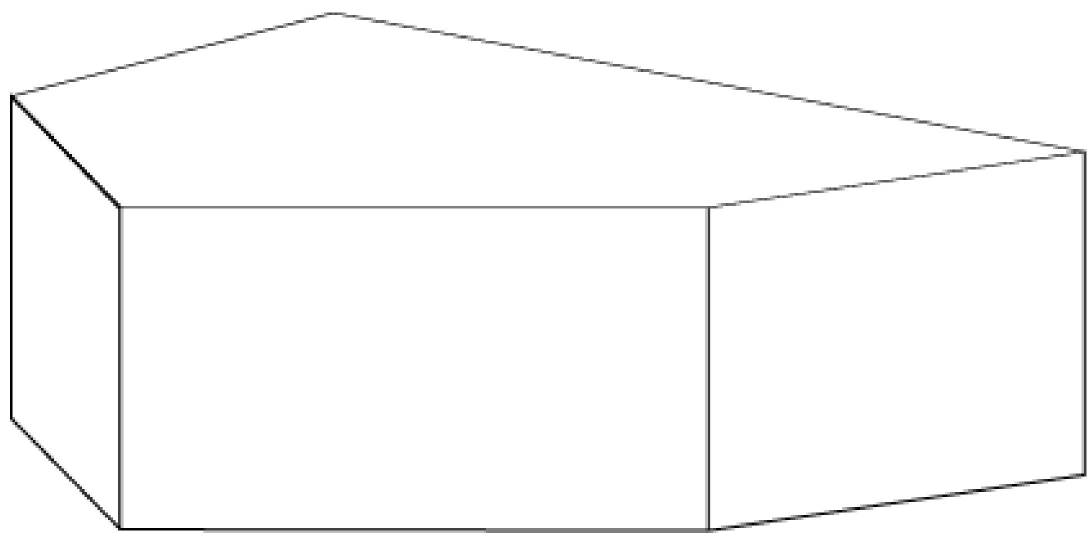

***Figure 12*. An example pentagonal prism. The actual stimuli were random-dot displays of such prisms, but contours are shown here for clarity in print.**

The height of all prisms was 4 cm, but the pentagonal faces of the prisms were asymmetric, so quantities like object width and depth cannot be specified as simply as for the objects used in the TTC study. Thus, I will give the ranges of side lengths to specify the relative size of the objects. The sides of the pentagonal faces of the prisms ranged 3.4–11.9 cm. Participants were instructed to press the up and down arrow keys on a keyboard to adjust the aspect ratio of a two-dimensional response figure to match the shape of the cross-section of the prism. This response figure was oriented to match the orientation of the prisms at the midpoint of rotation. The aspect ratio of a prism was defined as the ratio of its maximum extent in the depth dimension to its maximum horizontal extent while at this orientation. Side lengths were selected from the range above to produce prisms with aspect ratios of 0.8, 0.9, 1.0, 1.1, or 1.2. Once satisfied with their adjustments to the response figure, participants pressed the space bar to enter the response and proceed to the next trial.

Results. We expect that errors in aspect ratio judgments will be reduced for the condition or conditions that presented relevant visual information. We calculated the aspect ratios of participants' entered response figures and computed error from the actual aspect ratios (with negative error scores corresponding to an underestimation of depth)., Performance in the combined condition exhibited the least error, followed by disparity-only, and then flow-only. We ran a repeated-measures ANOVA on these error values with visual condition (flow-only, disparity-only, and combined), rotation amount (15, 45, and 75°), and aspect ratio (0.8, 0.9, 1.0, 1.1, and 1.2) as factors. There were main effects of visual condition ($F(2, 18) = 47.02$, $p < .001$) and aspect ratio ($F(4, 36) = 114.00$, $p < .001$), but not rotation. There were interactions between information condition and aspect ratio ($F(8, 72) = 4.10$, $p < .05$) and between rotation amount and aspect ratio ($F(8, 72) = 4.05$, $p < .05$). Contrasts showed that there was significantly less error in the disparity-only ($M = -0.14$, $SD = 0.11$) condition than the flow-only ($M = -0.22$, $SD = 0.09$) condition ($F(1, 9) = 22.03$, $p < .001$), and in turn there was significantly less error in the combined ($M = -0.07$, $SD = 0.10$) condition than the disparity-only condition ($F(1, 9) = 22.34$, $p < .001$).

Error mostly came in the form of underestimation of aspect ratio, which corresponds to an underestimation of depth. We expected that perception of depth might be compressed in the flow-only condition because it lacked disparity information. This would result in greater errors for objects with greater aspect ratios, similar to what was observed in conditions in previous studies that provided less than 45° of rotation. Thus, we decided to carry out further analysis to fully understand how error varied across conditions. For each participant we calculated the average judged aspect ratio for objects of each actual aspect ratio in each instance of visual condition × rotation amount. For each instance of visual condition × rotation amount, we regressed participants' average judgments of aspect ratio against the actual aspect ratios and calculated the resulting slopes of the fits. A slope of 1 would indicate that compression of depth did not occur. For slope values less than 1, the lesser the value of the slope, the greater the compression. Example data can be seen in Figure 13. Similarly, we compared the intercepts against a value of 0.

We ran a repeated-measures ANOVA on these slopes with visual condition (flow-only, disparity-only, and combined) and rotation amount (15, 45, and 75°) as factors (Table 2). There were main effects of visual condition ($F(2, 18) = 5.61$, $p < .05$) and rotation ($F(2, 18) = 11.78$, $p < .05$), but no interaction. Contrasts showed a significant difference between the combined and disparity-only ($F(1, 9) = 16.46$, $p < .05$) conditions, but no difference between flow- and disparity-only. Similarly, contrasts showed a significant difference between the 45 and 75° ($F(1, 9) = 16.12$, $p < .05$) conditions, but not between 15 and 45°, although this result approached significance.

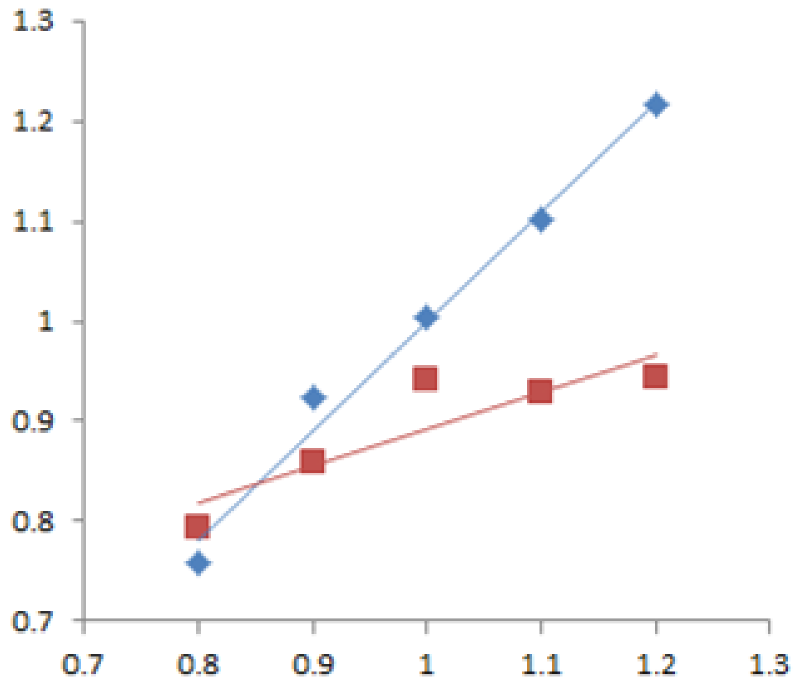

***Figure 13*. Example regressions of sample data. The blue markers (slope = 1.09) shows data from a condition where space was not compressed and the red markers (slope = 0.37) show data from a condition where space was compressed.**

Table 2

Average Slope Across Participants for Each Visual Condition × Rotation Pair

Visual Condition	15°	45°	75°
Flow-only	0.423 (0.339)	0.559 (0.254)	0.728 (0.347)
Disparity-only	0.479 (0.202)	0.608 (0.323)	0.679 (0.376)
Combined	0.720 (0.242)	0.804 (0.295)	1.025 (0.289)

***Note*. The numbers in parentheses indicate standard deviation.**

We ran one-sample t-tests on the slopes for each visual condition × rotation pair to test difference from a slope of 1. In the flow-only condition, significant differences were found for 15° ($t(9) = -5.38$, $p < .001$), 45° ($t(9) = -5.50$, $p < .001$), and 75° ($t(9) =$

−2.48, $p < .05$). In the disparity-only condition, significant differences were found for 15° ($t(9) = −8.15$, $p < .001$), 45° ($t(9) = −3.84$, $p < .05$), and 75° ($t(9) = −2.70$, $p < .05$). In the combined condition, a significant difference was found for 15° ($t(9) = −3.66$, $p < .05$), but not 45° or 75°.

We also ran a repeated-measures ANOVA on the intercepts with visual condition (flow-only, disparity-only, and combined) and rotation amount (15, 45, and 75°) as factors (Table 3). There was a main effect of rotation ($F(2, 18) = 12.29$, $p < .001$), but no main effect of visual condition (although it approached significance) and no interaction. Contrasts showed a significant difference between 45 and 75° ($F(1, 9) = 15.94$, $p < .05$), but not between 15 and 45°. Similarly, contrasts showed a significant difference between the disparity-only and combined ($F(1, 9) = 12.12$, $p < .05$) conditions, but not between flow-only and disparity-only.

Table 3

Average Intercept Across Participants for Each Visual Condition × Rotation Pair

Visual Condition	15°	45°	75°
Flow-only	0.353 (0.281)	0.201 (0.201)	0.060 (0.300)
Disparity-only	0.383 (0.223)	0.266 (0.314)	0.182 (0.378)
Combined	0.223 (0.208)	0.141 (0.270)	−0.111 (0.251)

***Note*. The numbers in parentheses indicate standard deviation.**

We ran one-sample t-tests on the intercepts for each visual condition × rotation pair to test difference from an intercept of 0. In the flow-only condition, significant differences were found for 15° ($t(9) = 3.96$, $p < .05$) and 45° ($t(9) = 3.16$, $p < .05$), but not 75°. In the disparity-only condition, significant differences were found for 15° (t(9) =

5.43, $p < .001$), 45° ($t(9) = 2.67$, $p < .05$), but not 75°. In the combined condition, a significant difference was found for 15° ($t(9) = 3.40$, $p < .05$), but not 45° or 75°.

Finally, we ran a repeated-measures ANOVA on the R^2 values with visual condition (flow-only, disparity-only, and combined) and rotation amount (15, 45, and 75°) as factors (Table 4). There was a main effect of rotation ($F(2, 18) = 4.37$, $p < .05$), but no main effect of visual condition (although it approached significance) and no interaction. There were no significant contrasts.

Table 4

Average R^2 Across Participants for Each Visual Condition × Rotation Pair

Visual Condition	15°	45°	75°
Flow-only	0.569 (0.312)	0.725 (0.255)	0.756 (0.191)
Disparity-only	0.597 (0.318)	0.677 (0.311)	0.790 (0.220)
Combined	0.799 (0.150)	0.851 (0.135)	0.880 (0.092)

***Note*. The numbers in parentheses indicate standard deviation.**

Discussion. As expected, errors were smallest in the combined condition. However, there was not a main effect of rotation in the error data. The effects of rotation are seen in the results of the regressions, though. The slope for each visual condition × rotation pair was significantly different from 1, except for 45° and 75° in the combined condition, as expected. This demonstrates that compression occurred in all conditions except when rotation was greater than or equal to 45° in the combined condition. The intercepts were significantly different from 0 in all visual conditions with only 15° of rotation, and not different from 0 in all visual conditions with 75° of rotation. With 45° of rotation, intercepts are significantly different from 0 in the flow- and disparity-only conditions, but not in the combined condition. There was also a main effect of rotation on the R^2 values, with greater R^2 values corresponding to greater rotation amounts.

When both flow- and disparity-based information were available, performance was better than with either source of information alone, and metric shape was perceived when 45° or more of rotation was provided in that combined condition. This raises the question of how these various sources of information are used in conjunction to yield accurate shape perception. There are a number of models of cue combination for perceiving properties of the environment, not just in vision but in all modalities, even across modalities. However, most models follow the same basic idea of a weighted linear combination of cues, regardless of sensory modality or property of the environment. Let's use perceiving the size of an object as an example. There are multiple visual cues about an object's size, and if an observer picked up the object or otherwise interacted with it, there would be more cues from other modalities. In most cue combination models, each cue produces an estimate of size and the weights of each cue are inversely proportional to the variance of that cue. In this way, the variance of the resulting linear combination is minimized. In a number of circumstances, such models predict human behavior (Ernst & Banks, 2002; Toscano & McMurray, 2011). However, such a strategy would only produce accurate perception under conditions that result in variance being the major source of error. If the individual estimates are systematically biased, reducing their error will be largely unproductive. This is the case here, as depth is underestimated when only one cue is present, regardless of which cue it is. The magnitude of a linear combination of cues is bound by the magnitudes of the individual cues, but human performance in Experiment 1 was best when all cues were present and the resulting judgments of depth exceeded those made when any individual cue was presented in isolation. Thus, an alternative model is necessary. R. Foster, Fantoni, Caudek, & Domini (2011) developed a model for depth perception that accounts for this. Instead of multiple cues each yielding independent estimates of depth that are then combined, the cues are combined to yield the local affine structure, analogous to a depth map. In this way, more information does not yield more estimates of depth, it yields more recovered depth in the single estimate.

Specifically, this model predicts that $K_c = \sqrt{K_v + K_d}$ where K_c, K_v, and K_d correspond to the slopes of the linear functions relating recovered and distal depth for the combined, flow-only, and disparity-only conditions, respectively. We calculated predictions of K_c for each visual condition × rotation pair, for each participant, using the measured values of K_v and K_d in the above equation, and compared these to the measured values of K_c. The mean predicted value of K_c was 0.88 (SD = 0.31) and the mean measured value of K_c was 0.85 (SD = 0.30). We ran a paired-samples t-test on these predicted and measured values of K_c and did not find a significant difference.

Our data seems to support the model of R. Foster et al. (2011). Their model is intrinsically tied to static disparity and its combination with optic flow. However, the presence of both flow and disparity simultaneously is not the only difference between the combined condition and the other visual conditions. The combined condition also introduces IOVD. Thus, further work is necessary to determine whether it is the combination of static disparity and optic flow or if it is IOVD that underlies metric shape perception. We addressed this in Experiment 2.

Experiment 2. For this experiment, we created displays that presented continuous flow-based information, as well as static disparity, but not CDOT or IOVD. That is, static stereo is preserved but dynamic stereo is eliminated. This was accomplished by taking the flow-only condition of Experiment 1 and replacing every few frames with the corresponding frame from a display of the same object from the combined condition. Thus, one eye received a continuous display of a rotating polyhedron and the other received static images of this object every few frames. When viewed binocularly, a continuously rotating object is perceived, and the only noticeable effect of adding input to the second eye every few frames is an increase in luminance for those frames. We initially pilot-tested this display with a stereo frame every three frames, but we were concerned that this alone wouldn't be sufficient to make a determination. By only presenting stereo information every three frames, we disrupted the continuity of stereo information to eliminate CDOT and IOVD, but this also meant that there was only one third as much static disparity information as in the combined condition from Experiment 1, so if we measured a decrease in performance, it could be due to this decrease in the total quantity of static disparity, not the elimination of IOVD. Thus, we ran the experiment with stereo intervals of 3, 5 and 7 frames. Thus, if performance declined more as the interval between stereo frames increased, we could conclude that this decline was due, at least in part, to decreases in the amount of static disparity available. If this decline did not vary with stereo interval, we could conclude that it was the lack of dynamic stereo information that led to the decline, not the reduced static disparity.

Methods. *Participants*. Twelve adults (8 female and 4 male, aged 21–28 years) were recruited to participate in this study. The participants had normal or corrected-to-normal vision, with stereoacuity of at least 80 arcsec crossed disparity as measured by the Stereo Fly Test (Stereo Optical Company, Inc.). We selected participants who did not participate in Experiment 1 to prevent prior knowledge of the range of aspect ratios from influencing responses. All participants gave their informed consent prior to participation. All procedures were approved by and conform to the standards of the Indiana University Institutional Review Board.

Stimuli and Procedure. Stimuli were similar to those used in Experiment 1, with one major difference in visual information condition. The only visual information condition was an otherwise flow-only display that had every few frames removed and replaced with frames from a combined display. If viewed with the left eye, it was exactly like the flow-only display, but if viewed with the right eye, the object was only displayed every few frames. Thus, monocular flow was available throughout and static disparity was available every few frames. Again, the object depicted was an asymmetric pentagonal prism with an aspect ratio of 0.8, 0.9, 1.0, 1.1, or 1.2 continuously rotating back and forth about a vertical axis through the center of the prism for the duration of the trial.

These perturbing displays are taxing on the eyes so we wanted to reduce the number of trials. To do so, we removed the 45° condition and just tested < 45° and > 45° conditions. We wanted the end points of rotation to always be a stereo frame, so we could only use total numbers of frames that were divisible by the interval between stereo frames. This resulted in slightly different rotation amounts depending on the interval between stereo frames. We also brought the < 45° and > 45° conditions closer together, so when the interval was 3 the rotation amounts were 27 and 66°, when the interval was 5 the rotation amounts were 25 and 65°, and when the interval was 7 the rotation amounts were 28 and 63°. As in Experiment 1, participants were instructed to press the up and down arrow keys on a keyboard to adjust the aspect ratio of a two-dimensional response figure to match the shape of the cross-section of the prism. Once satisfied with the response figure, participants pressed the space bar to enter their response and proceed to the next trial. Trials were blocked by stereo interval and the order of blocks was always 7 frames, 5 frames, 3 frames. This prescribed order was used to prevent a confound. It is possible that with a small stereo interval, some sort of dynamic stereo information, analogous to apparent motion, would be available. If there was indeed some form of dynamic stereo with a small interval between frames, we did not want participants experiencing this first, become calibrated to the space, and let this affect their judgment in trials with a large interval between stereo frames. We were aware of potential practice effects and were thus prepared to counterbalance this by running another group of participants in the order of 3, 5, 7 if participants performed better with an interval between stereo frames of 3.

Results. As in Experiment 1, we calculated the aspect ratios of participants' entered response figures, computed error from the actual aspect ratios, and ran a repeated-measures ANOVA on these error values with visual condition (3-frame, 5-frame, and 7-frame), rotation amount (<45° and >45°), and aspect ratio (0.8, 0.9, 1.0, 1.1, and 1.2) as factors. There was a main effect of aspect ratio ($F(4, 44) = 56.10$, $p < .001$), but not rotation or visual condition, and no interactions. The average absolute error was −0.155 in the 3-frame condition (SD = 0.118), −0.148 in the 5-frame condition (SD = 0.137), and −0.151 in the 7-frame condition (SD = 0.158).

As in Experiment 1, for each instance of visual condition × rotation amount, we regressed participants' average judgments of aspect ratio against the actual aspect ratios and calculated the resulting slopes of the fits. We ran a repeated-measures ANOVA on these slopes with visual condition (3, 5, and 7 frames) and rotation amount (<45 and >45°) as factors. There were no main effects and no interaction. We also ran a repeated-measures ANOVA on the intercepts with visual condition (3, 5, and 7 frames) and rotation amount (<45° and >45°) as factors. There was a main effect of rotation ($F(1, 11) = 13.47$, $p < .05$), but no main effect of visual condition and no interaction. Finally, we ran a repeated-measures ANOVA on the R^2 values with visual condition (3, 5, and 7 frames) and rotation amount (<45° and >45°) as factors. There were no main effects, but there was an interaction between visual condition and rotation ($F(2, 22) = 3.81$, $p < .05$).

There was no difference in error across stereo intervals, so we averaged the data across the 3-frame, 5-frame, and 7-frame conditions (mixed stereo) and compared these data to the combined condition of Experiment 1, in which there was stereo information available of every frame. We ran a mixed ANOVA on the error data with rotation amount (<45 and >45°) and aspect ratio (0.8, 0.9, 1.0, 1.1, and 1.2) as within-subjects factors and visual condition (mixed stereo and combined) as a between-subjects factor. There were main effects of visual condition ($F(1, 20) = 5.35$, $p < .05$) and aspect ratio ($F(4, 80) = 8.94$, $p < .001$), and an interaction between aspect ratio and rotation ($F(4, 80) = 5.73$, $p < .001$).

We also compared slope, intercept, and R^2 between the mixed stereo and combined conditions. First, we ran a mixed ANOVA on the slopes with visual condition (mixed stereo and combined) as a between –subjects factor and rotation amount (<45 and

>45°) as a within-subjects factor. There were main effects of visual condition ($F(1, 20) = 4.57$, $p < .05$) and rotation ($F(1, 20) = 24.04$, $p < .001$), but no interaction. Then we ran the same analysis on the intercepts. There was a main effect of rotation ($F(1, 20) = 28.24$, $p < .001$), but no interaction. Lastly, we ran the analysis on the R^2 values. There were main effects of visual condition ($F(1, 20) = 6.46$, $p < .05$) and rotation ($F(1, 20) = 4.75$, $p < .05$), but no interaction.

Discussion. Performance with all stereo intervals was significantly worse than the combined condition of Experiment 1. However, differences in the stereo interval, and thus the total number of stereo frames, had no effect on error, slope, intercept, or R^2. Thus, the superior performance in the combined condition appears to be due to the presence of IOVD, not static stereo. Thus, we conclude that although the manner in which the model of R. Foster et al. (2011) combines cues is superior at predicting judgements of shape, the model does not actually capture the way in which visual information is used to produce these judgments. Static stereo is ineffective. Dynamic stereo, in the form of IOVD is required.

Conclusion

The environment in which humans live is dynamic. Motion is ubiquitous, so accurate perception of the environment inevitably must include sensitivity to this. Perception using motion information goes beyond this, though. In addition to informing humans about how the environment is changing, it aids processes that are usually thought of as static, such as perception of space and shape. In fact, without retinal motion the visual system has difficulty interpreting stimuli (Riggs et al., 1953).

Patterns of retinal stimuli are exceedingly complex because of environmental motion, as well as a number of forms of observer motion. Body, head, and eye movements all complicate patterns of motion on the retina, but these also yield information about the environment. Motion information comes from both optic flow and binocular disparity. Either flow- or disparity-based information may be used for most tasks by people with fully intact vision, although many tasks have a preferred source that allows for high performance alone.

We found that people were better at discriminating between the TTC of two objects moving at high velocity with flow-based information alone then with disparity-based information alone. Similarly, we found discrimination when viewing slow objects was better with disparity-based information. However, in each case, the less informative source of motion information was still informative as participants performed above chance with that cue alone. In both cases, performance with both information sources available was equal to performance with only the superior one, so there is no evidence that these sources are combined. That is, it appears that humans just rely on whichever is superior given the current conditions. However, due to spatial constraints imposed by the disparity-only condition, the displays with the fast stimuli were shorter than those with slow stimuli, so it was possible that the poor performance was because there was not enough disparity-based information to be reliable. In a second experiment, we tested fast stimuli with longer duration and found no improvement in performance, so the result that flow-based information is superior to disparity-based information when viewing fast motion was confirmed.

The ability to perceive TTC is frequently exploited for approach behaviors, i.e. tasks that require timely approach to a target with smooth deceleration resulting in soft contact, such as walking and braking. Like those examples, reaching to targets requires approach with smooth deceleration to a target, but it requires bringing the hand to a target instead of bringing the body to a target. Thus, traditional τ information would not be useful because it is eye-centric, i.e. it specifies the TTC of the eye, not the hand, with an object. Attempts have been made to identify some sort of hand-τ for tasks like reaching and catching, but ultimately candidate optic variables were not successful because they were still eye-centric. Even ones that successfully predicted behavior required assumptions that were not at all representative of real-world behaviors, such as the hand being in the same depth plane as the eye so that eye-centric information would be approximately correct for the hand (Bootsma & Oudejans, 1993; Carnahan & McFadyen, 1996; Hopkins, Churchill, Vogt, & Rönnqvist, 2004; Savelsbergh, Whiting, & Bootsma, 1991; Savelsbergh, Whiting, & Pijpers, 1992; Savelsbergh, Whiting, Burden, & Bartlett, 1992; Wallace, Stevenson, Weeks, & Kelso, 1992; Zaal & Bootsma, 1995). Eventually a hand-centric τ was identified and binocular disparity was key (Anderson & Bingham, 2010, 2011) because the act of bringing the hand to the same spatial location as a target invariably results in matching the binocular disparity of the hand and target. Interestingly, previous work showed that eye-τ is used during the initial, rapid portion of approach and then hand- τ is used during the final, slower portion of approach (Fath et al., 2014), which is compatible with how speed relates to information used in our TTC result.

Using a manual coordination task, we also showed how disparity-based information alone is sufficient to guide perception of, and coordination with, laterally moving objects with no decrease in performance compared to normal viewing conditions that present all sources of motion information. This is true despite the greater latencies when processing disparity-based information about lateral motion than when processing flow-based information about lateral motion. This is because the increased latency affects perception of both objects equally, so relative phase is unaffected.

It is obvious that motion information would be crucial to perception of and interaction with our dynamic environment, but we also showed how important motion information is to the perception of static properties like object shape. Specifically, we presented participants with rotating polygonal prisms and had them make judgments of shape. As in the other experiments, these stimuli were presented with flow-based information, disparity-based information, or both. Due to the results of prior experiments, we also manipulated rotation amount, using 15, 45, and 75°. The errors of participants' shape judgments were smallest in the combined condition, but disparity-only had smaller errors than flow-only. One source of error was compression of depth, which was observed in all conditions except with 45 or 75° of rotation in the combined condition.

Because performance was best in the combined condition, it was initially unclear whether this was because both flow and disparity-based information are available together and can be combined, or whether participants used IOVD, which was only available in the combined condition. We tested this in a second experiment. If these cues are combined, most cue combination models would not work because they rely on a weighted linear combination of cues. This bounds the resulting estimate to within the range of the individual estimates. However, our data was outside this range, so these models are incompatible with our results.

However, the model of R. Foster et al. (2011) combines information in a way that is consistent with our data. It combines flow-based information with static disparity, so we presented participants with a display that provided flow and static disparity, but not CDOT or IOVD. Errors were higher than those in the combined condition of the first experiment, so we conclude that IOVD is used, not a combination of flow and static disparity.

Because IOVD is difficult or impossible to isolate, its utility cannot be easily identified. In other domains, accurate performance can be seen with some other single source of information, so IOVD's role cannot be identified through elimination of other sources, as was the case in this study. This result is encouraging, though, because it reinforces the scarce studies that also support human use of IOVD. Thus, its utility should be under consideration in future studies attempting to establish what source of information underlies a perceptual task.

With advancements in the study of the psychophysics of flow- and disparity-based information, we now have a greater understanding of the spatial, temporal, and spatiotemporal aspects that govern their utility and we were able to develop and test hypotheses about their roles in perception. Here I have revisited several well-researched perceptual and perceptuomotor tasks and investigated the roles of flow- and disparity-based motion information in their execution. Whether perceiving a spatiotemporal property of an object, like TTC, or a spatial property, like shape, the perceptual process is spatiotemporal. We demonstrated that, depending on the conditions, either optic flow or CDOT is used to perceive the TTC of an object, both of which are inherently spatiotemporal. Specifically, optic flow is the changes in retinal position over time and

CDOT is the changes in the difference in retinal positions over time across the two eyes. Furthermore, which of these sources of information is used is dependent on the target object's rate of change of position over time. When perceiving an object's shape, IOVD is used. This is the difference between the optic flow patterns of the two eyes. For this to be fully effective, an observer needs to experience 45° of continuous perspective change over time, whether due to observer motion or object motion. This work has shed light on both the principles that underlie motion perception and the role of motion perception in other tasks.

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University of Leeds, Institute of Psychological Sciences
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Faculty advisor: Prof. Mark Mon-Williams

Teaching Experience

Instructor

Spring, 2016 Research Methods, University of Southern Mississippi
Spring, 2016 Statistics for Behavioral Sciences, University of Southern Mississippi
Fall, 2016 History & Systems of Psychology, University of Southern Mississippi
Fall, 2016 Statistics for Behavioral Sciences, University of Southern Mississippi
Fall, 2016 General Psychology, University of Southern Mississippi
Spring, 2013 Methods of Experimental Psychology, Indiana University

Associate Instructor

Summer, 2015 Abnormal Psychology, Indiana University
Spring, 2014 Computation in Cognitive & Info Sciences, Indiana University
Spring, 2014 Programming for Cognitive & Info Sciences, Indiana University
Fall, 2013 Math & Logic for Cognitive & Info Sciences, Indiana University
Fall, 2012 Math & Logic for Cognitive & Info Sciences, Indiana University

Teaching Assistant

Fall, 2008 Remedial Math, Doyle Middle School, Troy, NY

Awards, Honors, and Fellowships

College of Arts and Sciences Dissertation Year Fellowship, Indiana University, 2015
National Science Foundation IGERT Fellowship Extension, Indiana University, 2014
Cognitive Science Supplemental Research Fellowship, Indiana University, 2014
Cognitive Science Supplemental Research Fellowship, Indiana University, 2013
National Science Foundation IGERT Fellowship, Indiana University, 2010
President's Scholarship, Rensselaer Polytechnic Institute, 2007
Rensselaer Alumni Scholarship, Rensselaer Polytechnic Institute, 2007

Publications

Fath, A. J., Snapp-Childs, W., Kountouriotis, G. K., & Bingham, G. P. (2016). Binocular perception of 2D lateral motion and guidance of coordinated motor behavior. Perception, *45*(4), 466–473. doi:10.1177/0301006615614664

Coats, R., **Fath, A. J.**, Astill, S., & Wann, J. P. (2016). Eye and hand movement strategies in older adults during a complex reaching task. Experimental Brain Research, *234*(2), 533–547. doi:10.1007/s00221-015-4474-7

Snapp-Childs, W., **Fath, A. J.**, Watson, C. A., Flatters, I., Mon-Williams, M., & Bingham, G. P. (2015). Training to improve manual control in 7–8 and 10–12 year old children: Training eliminates performance differences between ages. Human Movement Science, *43*, 90–99. doi:10.1016/j.humov.2015.07.006

Fath, A. J., Marks, B. S., Snapp-Childs, W., & Bingham, G. P. (2014). Information and control strategy to solve the degrees-of-freedom problem for nested locomotion-toreach. Experimental Brain Research, *232*(12), 3821–3831. doi:10.1007/s00221-014-4072-0

Bingham, G. P., Snapp-Childs, W., **Fath, A. J.**, Pan, J. S., & Coats, R. O. (2014). A geometric and dynamic affordance model of reaches-to-grasp: Men take greater risks than women. Journal of Experimental Psychology: Human Perception and Performance, *40*(4), 1542–1550. doi:10.1037/a0036825

Coats, R. O., Wilson, A. D., Snapp-Childs, W., **Fath, A. J.**, & Bingham, G. P. (2014). The 50s cliff: Perceptuo-motor learning rates across the lifespan. PLOS ONE, *9*(1): e85758. doi:10.1371/journal.pone.0085758

Snapp-Childs, W., Flatters, I., **Fath, A. J.**, Mon-Williams, M. A., & Bingham, G. P. (2014). Training compliance control yields improvements in drawing as a function of Beery scores. PLOS ONE, *9*(3): e92464. doi:10.1371/journal.pone.0092464

Fath, A. J., & Fajen, B. R. (2011). Static and dynamic visual information about the size and passability of an aperture. Perception, *40*(8), 887–904. doi:10.1068/p6917

<u>Submitted Publications</u>
Fath, A. J., Lind, M., & Bingham, G. P. (2016). Differences between perception of time-to-contact of slow- and fast-moving objects using disparity and flow information. Manuscript submitted for publication.

Fath, A. J., Wang, X., Lind, M., & Bingham, G. P. (2016). Continuous perspective change with stereo information yields metric shape perception. Manuscript submitted for publication.

Wang, X. M., **Fath, A. J.**, Snapp-Childs, W., Lind, M., & Bingham, G. P. (2016). A new slant on "two eyes are better than one": Large continuous perspective changes (>45°) allow metric slant perception using cyclopean or stereo motion. Manuscript in preparation.

Jamieson, E., Mushtaq, F., **Fath, A. J.**, Bingham, G. P., Culmer, P., Wilkie, R. M., & Mon-Williams, M. A. (2015). Exploring disruption as a force for good in motor learning. Manuscript submitted for publication.

Manuscripts in Preparation

Snapp-Childs, W., **Fath, A.**, Wang, X. M., & Bingham, G. P. (2016). Training compliance control across different scales of movement yields general learning in children. Manuscript in preparation.

Snapp-Childs, W., **Fath, A.**, Wang, X. M., & Bingham, G. P. (2016). The role of prospective control in training manual compliance. Manuscript in preparation.

Published Abstracts

Wang, X., **Fath, A. J.**, Snapp-Childs, W., Lind, M., & Bingham, G.P. (2016). Inhomogeneity of perceived slants with different motion-based visual information. Journal of Vision, *16*, 654. doi:10.1167/16.12.654

Fath, A. J., Lind, M., & Bingham, G. P. (2015). Comparison of monocular and stereo sources of motion information about time-to-contact of slow and fast objects. Journal of Vision, *15*, 828. doi:0.1167/15.12.828

Snapp-Childs, W., **Fath, A. J.**, & Bingham, G. P. (2015). Training of compliance control across different scales of movement yields general learning in children. Journal of Vision, *15*, 1154. doi:10.1167/15.12.1154.

Coats, R., **Fath, A. J.**, Astill, S., & Wann, J. (2015). Eye-hand coordination strategies in older adults. Journal of Vision, *15*, 1152. doi:10.1167/15.12.1152

Wang, X. M., **Fath, A. J.**, Lind, M., & Bingham, G. P. (2015). A new slant on “two eyes are better than one”: Large continuous perspective changes (_ 45_) allow metric slant perception using cyclopean (or stereo-) motion. Journal of Vision, *15*, 724. doi:10.1167/15.12.724

Fath, A. J., Snapp-Childs, W., Watson, C., & Bingham, G. P. (2014). Training compliance control improves manual actions in older children. Journal of Sport & Exercise Psychology, *36*, 66.

Fath, A. J., Marks, B. S., & Bingham, G. P. (2013). Response to perturbation in constant tau-dot versus constant proportional rate models of visually guided braking. Journal of Vision, *13*(9), 747. doi:10.1167/13.9.747

Coats, R., Wilson, A. D., Snapp-Childs, W., **Fath, A. J.**, & Bingham, G. P. (2013). The 50s cliff: Perceptuo-motor learning rate across the lifespan. Journal of Vision, *13*(9), 483. doi:10.1167/13.9.483

Snapp-Childs, W., Flatters, I., **Fath, A. J.**, Mon-Williams, M. A., & Bingham, G. P. (2013). Training of compliance control in children yields improvements in handwriting. Journal of Vision, *13*(9), 489. doi:10.1167/13.9.489

Fath, A. J., & Bingham, G. P. (2012). One thing at a time: Sequential coordination in visual guidance of locomotion-to-reach. Journal of Vision, *12*(9), 194. doi:10.1167/12.9.194

Fath, A. J., & Fajen, B. R. (2010). Static and dynamic information about the size and passability of apertures. Journal of Vision, *10*(7), 1025. doi:10.1167/10.7.1025

<u>Other Published Work</u>
Changizi, M. A. (2011). Harnessed: How language and music mimicked nature and transformed ape to man. BenBella Books. Author spends two pages discussing unpublished data of mine, which is credited to me in-text.

Presentations

Wang, X., **Fath, A. J.**, Snapp-Childs, W., Lind, M., & Bingham, G.P. (May, 2016). Inhomogeneity of perceived slants with different motion-based visual information. Poster presented at the 16th annual meeting of the Vision Sciences Society, St. Pete Beach, FL.

Fath, A. J. (2015, December). Functional roles of optical information about motion. Invited lecture given at Indiana University Cognitive Lunch, Bloomington, IN.

Fath, A. J. (2015, September). Disruption of color perception with low-pressure sodium vapor lamp. Invited lecture given at a meeting of the Indiana University Student Organization for Cognitive Science, Bloomington, IN.

Fath, A. J., Lind, M., & Bingham, G. P. (2015, July). Flow- and disparity-based information about time-to-contact of slow and fast objects. Poster presented at the Indiana University Vision Science Fair, Bloomington, IN.

Bingham, G. P., Lind, M., **Fath, A. J.**, Wang, X. M. (2015, May). Perceiving affine and metric *3*D surfaces using multiple motion systems. Invited lecture given at a meeting of the Department of Psychology, University of Connecticut, Storrs, CT.

Fath, A. J., Lind, M., & Bingham, G. P. (2015, May). Comparison of monocular and stereo sources of motion information about time-to-contact of slow and fast objects. Poster presented at the 15th annual meeting of the Vision Sciences Society, St. Pete Beach, FL.

Snapp-Childs,W., **Fath, A. J.**, & Bingham, G. P. (2015, May). Training of compliance control across different scales of movement yields general learning in children. Poster presented at the 15th annual meeting of the Vision Sciences Society, St. Pete Beach, FL.

Coats, R., **Fath, A. J.**, Astill, S., & Wann, J. (2015, May). Eye-hand coordination strategies in older adults. Poster presented at the 15th annual meeting of the Vision Sciences Society, St. Pete Beach, FL.

Wang, X. M., **Fath, A. J.**, Lind, M., & Bingham, G. P. (2015, May). A new slant on "two eyes are better than one": Large continuous perspective changes (>45°) allow metric slant perception using cyclopean (or stereo-) motion. Poster presented at the 15th annual meeting of the Vision Sciences Society, St. Pete Beach, FL.

Fath, A. J., Snapp-Childs, W., Kountouriotis, G., & Bingham, G. (2015, April). Monocular and stereo information about time-to-contact of approaching objects. Poster presented at the 2015 IGERT Showcase, Bloomington, IN.

Fath, A. J., Marks, B., & Bingham, G. P. (2014, July). Visual guidance of deceleration during approach behaviors. Poster presented at the Indiana University School of Optometry Vision Expo, Bloomington, IN.

Fath, A. J., Snapp-Childs, W., Watson, C., & Bingham, G. (2014, June). Training compliance control improves manual actions in older children. Poster presented at the North American Society for Psychology of Sport and Physical Activity 2014 Conference, Minneapolis, MN.

Fath, A. J., Snapp-Childs, W., Watson, C., & Bingham, G. (2014, April). Training compliance control improves manual actions in children with developmental coordination disorder. Poster presented at the 2014 IGERT Showcase, Bloomington, IN.

Fath, A. J. (2014, April). Disruption of color perception in single-wavelength environments. Invited lecture given at a meeting of the Indiana University Student Organization for Cognitive Science, Bloomington, IN.

Fath, A. J., Marks, B., & Bingham, G. (2013, May). Response to perturbation in constant tau-dot versus constant proportional rate models of visually guided braking. Poster presented at the 13th annual meeting of the Vision Sciences Society, Naples, FL.

Coats, R., Wilson, A. D., Snapp-Childs, W., **Fath, A. J.**, & Bingham, G. P. (2013, May). The *50*s cliff: Perceptuo-motor learning rate across the lifespan. Poster presented at the 13th annual meeting of the Vision Sciences Society, Naples, FL.

Snapp-Childs, W., Flatters, I., **Fath, A. J.**, Mon-Williams, M. A., & Bingham, G. P. (2013, May). Training of compliance control in children yields improvements in handwriting. Poster presented at the 13th annual meeting of the Vision Sciences Society, Naples, FL.

Fath, A. J., & Bingham, G. (2012, May). One thing at a time: Sequential coordination in visual guidance of locomotion-to-reach. Poster presented at the 12th annual meeting of the Vision Sciences Society, Naples, FL.

Fath, A. J., & Bingham, G. (2012, May). Initiation and coordination of visually guided locomotion-to-reach behavior. Poster presented at the 2nd annual Midwestern Cognitive Science Conference, Bloomington, IN.

Fath, A. J., & Bingham, G. (2012, April). Proportional rate control for the visual guidance of locomotion-to-reach. Poster presented at the 2012 IGERT Showcase, Bloomington, IN.

Fath, A. J., & Bingham, G. (2011, April). Coordination of visual-motor approach behaviors. Poster presented at the 2011 IGERT Showcase, Bloomington, IN.

Fath, A. J., & Fajen, B. (2010, May). Static and dynamic information about the size and passability of apertures. Poster presented at the 10th annual meeting of the Vision Sciences Society, Naples, FL.

Professional Activities & Affiliations

Reviewer, Quarterly Journal of Experimental Psychology, 2012
Student Member, North American Society for Psychology of Sport and Physical Activity, 2014
Graduate Student Affiliate, Association for Psychological Science, 2013
Predoctoral Member, Vision Sciences Society, 2010, 2012, 2013, 2015
Member, Pi Mu Epsilon National Mathematics Honor Society, 2008 – Present